Combating Terrorism Center
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SMALL GROUPS, BIG WEAPONS

THE NEXUS OF EMERGING TECHNOLOGIES AND WEAPONS OF MASS DESTRUCTION TERRORISM

Major Stephen Hummel and Colonel F. John Burpo | April 2020

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The views expressed in this report are the authors' and do not necessarily reflect those of the Combating Terrorism Center, Department of Chemistry and Life Science, United States Military Academy, 20th CBRNE Command, Defense Threat Reduction Agency, Department of Defense, or U.S. Government.

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Cover Photo: Three unmanned aerial systems (UAS) in flight at Edwards Air Force Base, California, in August 2019 (Staff Sgt. Rachel Simones/U.S. Air Force)

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Executive Summary

Historically, only nation-states have had the capacity and resources to develop weapons of mass destruction (WMD). This was due to the significant capital, infrastructure, and intellectual capacity required to develop and maintain a WMD program. This paradigm, however, is shifting. To be clear, non-state actors have been interested in WMD for decades. In fact, over a 26-year period, there were 525 incidents by non-state actors involving nuclear, biological, and chemical agents. But the scale of these incidents was relatively low level when compared to the impact of terrorist attacks using conventional weapons. However, this reality must be reexamined given the commercialization of emerging technologies that is reducing the financial, intellectual, and material barriers required for WMD development and employment.

This report serves as a primer that surveys the key challenges facing non-state actors pursuing WMD capabilities, and the potential for certain emerging technologies to help overcome them. While there are numerous examples of such technologies, this report focuses on synthetic biology, additive manufacturing (AM) (commonly known as 3D printing), and unmanned aerial systems (UAS).

There is a wide range of expert opinions regarding the dual-use nature of the technologies discussed in this report, the ease of their possible misuse, and the potential threats they pose. The varied opinions of scientists and government officials highlight the challenges these technologies pose to developing a cohesive strategy to prevent their proliferation for nefarious use by non-state actors. Much of the risk and threat associated with these dual-use technologies resides in the intent of the user.

Findings

This report finds that while the barrier for development is being reduced, the technologies' use in WMD development is not inevitable and still not without significant obstacles.

Nuclear Weapons: *The acquisition of special nuclear material remains the largest and nearly insurmountable hurtle.* While it is in theory possible to 3D print a gas centrifuge to separate uranium isotopes, doing so is not practical. These technologies could assist in the reprocessing of spent fuel rods for plutonium extraction. However, if significant quantities of special nuclear material were acquired, AM could assist in making the explosives and firing systems required to detonate a nuclear weapon while a UAS could be used as a delivery platform.

Chemical and Biological Weapons: *Where these technologies could have the greatest potential impact in the next five to 10 years is in the development and employment of both chemical and biological agents.* While the world has already witnessed terrorist organizations develop and employ both biological and chemical weapons agents, their employment has been limited. The use of AM and UAS would enable a chemical agent to be dispersed without the use of conventional explosives, such as mortars and artillery. In terms of biological weapons agents, the use of AM and UAS would additionally help dissemination. *It is, however, the commercialization of synthetic biology that may have the largest impact on accessibility and delivery.* Currently, researchers are able to *de novo* synthesize viruses, to include analogs of smallpox. And while many researchers are sensitive about the nature of their work, particularly its exploitation for developing a biological weapons agent, their techniques and tools are being commercialized. *In the next five to 10 years, it is likely that development of a biological weapon will not require the decades' worth of knowledge of a well-established researcher.* Instead, an undergraduate with minimal experience in a lab could purchase commercially available synthetic biology kits and materials to develop an agent or modify an existing agent to be more deadly or undetectable.

While this report focuses on synthetic biology, additive manufacturing, and unmanned aerial systems, these are certainly not the only technologies that reduce the barrier for WMD proliferation. As with any new technologies that emerge, it is important to ask of them: what about this technology can

potentially be used for terrorism? And specific to the challenges addressed by this report, can these technologies be used to proliferate and employ WMD? One also needs to ask if there is a means to limit the nefarious use of this technology by terrorists.

There is no silver-bullet solution to prevent terrorists from using these technologies in some form or another to develop and/or employ a weapon of mass destruction. *It is only through a whole-of-government approach at the local, state, and federal levels that prevention is possible.* The approach would require multiple lines of effort that are mutually supporting and focus on both prevention and response to an attack:

1. Enhance outreach and cooperation between consumers, the do-it-yourself communities, scientists, corporations, and foreign governments.
2. Address the dual-use nature of these technologies via export controls and other regulations.
3. Leverage these same technologies to improve response to a WMD incident, thereby enhancing deterrence.
4. Improve attribution for biological weapons by expanding existing databases to include agents modified by emerging synthetic biology tools.

"At the dawn of a new century, we find ourselves in a new arms race. Terrorists are racing to get weapons of mass destruction; we ought to be racing to stop them."

— Former U.S. Senator Sam Nunn, 2001[1]

"No one in this room can accurately predict the future, least of all me. The nature of war is never gonna change. But the character of war is changing before our eyes–with the introduction of a lot of technology, a lot of societal changes with urbanization and a wide variety of other factors."

— General Mark Milley, Association of the U.S. Army Convention, 2017[2]

Introduction

Historically, only nation-states have had the capacity and resources to develop and maintain a weapons of mass destruction (WMD) program, which according to U.S. Department of Defense Joint Publication 3-40 is defined as Chemical, Biological, Radiological, and Nuclear (CBRN) weapons or devices capable of a high order of destruction and/or causing mass casualties.[3] This paradigm was the result of the significant capital, infrastructure, and intellectual capacity required to develop and maintain a WMD program. These barriers to entry, however, have been disintegrating over the past few decades.

Although representing varying degrees of scale and effect, the 1995 sarin attack on the Tokyo subway, the 2001 anthrax letters in the United States, and the Islamic State's use of chemical weapons all illustrate the diminishing threshold for terrorist organizations to use WMD. Between 1996 and 2016, there were 525 WMD (18 nuclear, 107 biological, and 400 chemical) incidents.[4] Due to the lack of technical knowledge and skill required to create radiological dispersal devices, the authors did not include these types of devices.

The continued high number of terror attacks coupled with the democratization of scientific technology and the proven use of chemical weapons by the Islamic State in the past few years indicate a new paradigm. From 2014 through 2017, a total of 76 chemical weapons (chlorine and sulfur mustard) attacks occurred in Iraq and Syria.[5] Additionally, in June 2018, a Tunisian jihadi was arrested in Germany for making ricin.[6] The employment and development of WMD globally indicate that terrorist organizations will attempt to increase their sphere of influence and power through the development and possession of WMD.[7] This view was noted by Nicholas Rasmussen, former director of the National Counterterrorism Center, in January 2018 when he said, "One of the significant negative consequences of the conflict in Iraq and Syria has been that it has been a playground laboratory for ISIS and other extremist organizations to engage in efforts to refine their ability to use chemicals, toxins, other materials that would have a chemical or toxic effect on the battlefield. If they're doing that on the battlefield, and [have] done so with some effect … it's only reasonable to assume that they would take that knowledge and try to apply it to their terrorism agenda."[8]

1 Sam Nunn, "Our New Security Framework," *Washington Post*, October 8, 2001.

2 Ben Watson, "State of the Army," Defense One, October 2017.

3 "Joint Publication 3-40, Countering Weapons of Mass Destruction," United States Joint Chiefs of Staff, October 31, 2014, page I-1.

4 Gary Ackerman and Michelle Jacome, "WMD Terrorism: The Once and Future Threat," *PRISM* 7:3 (2018): pp. 23-36.

5 Columb Strack, "The Evolution of the Islamic State's Chemical Weapons Efforts," *CTC Sentinel* 10:9 (2017).

6 David Brennan, "Jihadist made Ricin with Web-bought Castor Beans Seeds, Police Say," *Newsweek*, June 14, 2018.

7 The Islamic State is not the first non-state actor to deploy chemical weapons. The Aum Shinrikyo cult released sarin gas on the Tokyo subway on March 20, 1995. Although more primitive, most terrorism researchers peg first use with the Tamil Tigers chemical attack in Sri Lanka in 1990.

8 Paul Cruickshank, "A View from the CT Foxhole: Nicholas Rasmussen, Former Director, National Counterterrorism Center," *CTC Sentinel* 11:1 (2018).

Given this growing concern, it is vital to understand how the proliferation of more easily accessible emerging technologies will reduce the barriers to developing WMD in the next five to ten years. Developments in the realms of synthetic biology, additive manufacturing (AM), and unmanned aerial systems (UAS), for example, represent three areas that require more attention. There are other emerging technologies, such as those in the cyber and chemical engineering realms, that could assist a terrorist in developing a WMD, however synthetic biology, AM, and UAS were chosen for closer analysis in this report due to their ease of availability and commercialization. These technologies are readily available worldwide and the applicability of their use in multiple domains of life is increasing.

Synthetic biology, AM, and UAS have clear societal benefits, to include the reduction of transportation costs, increased commerce, and the development of new medical treatments, respectively. At first glance, these technologies appear disparate. Their growth and development, however, are interlinked and highlighted by 3D-printed drones, bio-printing, and modifying organisms to produce molecules for polymers, such as goats that produce spider silk that is stronger than Kevlar.[9] Despite their clear benefits, however, these technologies can be and have been used by nefarious actors, specifically terrorists, in the development and deployment of WMD.

These emerging technologies can also increase terrorists' capabilities to avoid detection by authorities. The ability to prevent large-scale terrorist attacks has been historically dependent on the ability to interdict the terrorist network. Such interdiction can be achieved through communication, logistics, or operational nodes. Theoretically, the larger the network, the easier it is to infiltrate, attack, and prevent a terrorist plot from proceeding, since larger networks have more hubs, or points of centralized information, and according to "Attacking the Nodes of Terrorist Networks" by Tim Minor, "targeting nodes has proven effective at generating intelligence."[10] Emerging technologies, however, may reduce the necessary size of the network, making it possible for an individual to plan, resource, and deploy a WMD without significant resources or guidance from a larger organization.

Despite emerging technologies reducing fiscal, infrastructural, and intellectual barriers, the rapid proliferation of WMD is not necessarily assured. These technologies are dual-use, and while the potential exists from them to be used nefariously, currently there is a greater capacity to combat proliferation and mitigate the effects of WMD.

In order to investigate how evolving technologies might affect the capabilities of terrorists, this report examines the nexus of synthetic biology, additive manufacturing, and unmanned aerial systems with nuclear, biological, and chemical weapon agent proliferation. The report is delineated into two primary sections. The first section provides a brief history of synthetic biology, additive manufacturing, and unmanned aerial systems and discusses the relevance of these technologies today. With a clearer understanding of the proliferation of these technologies, the second section of the report examines the application of each method in the context of developing and employing a WMD. The report is intended to be a primer for both policymakers and scientists, highlighting both the benefits of these technologies to society and their pitfalls in relation to WMD proliferation.

9 Adam Rutherford, "Synthetic biology and the rise of the 'spider-goats,'" *Guardian*, January 14, 2012.

10 Tim Minor, "Attacking the Nodes of Terrorist Networks," *Global Security Studies* 3:2 (2012).

Background on Selected Emerging Technologies

In order to have a robust discussion about how emerging technologies may affect the proliferation of WMD, it is vital to understand the basics of these technologies. In this analysis, synthetic biology, additive manufacturing, and unmanned aerial systems serve as productive examples of technologies that terrorists may be able to exploit in the future. This section provides the background and context required to assess, in the next section, these technologies' relevancy to the WMD terrorism threat. As will be demonstrated below, advancements in these three areas are especially relevant because they have made it increasingly easy for terrorists to leverage these technologies to achieve their WMD objectives.

Synthetic Biology

"Synthetic biology is the rational design and construction of modified or new biological systems/organisms with desired functionality, or the synthesis of organisms *de novo*, accomplished via the application of engineering principles to make specific genetic changes using the techniques of molecular biology."[11] While the idea of synthetic biology may seem abstract to most, the concepts of deoxyribonucleic acid (DNA) recombination and cloning have existed for more than 150 years. In 1865, Gregor Mendel first demonstrated the effects of DNA recombination when he cross-pollinated different pea pod plants. In 1953, Rosalind Franklin, Maurice Wilkins, Francis Crick, and James Watson discovered the helical, three-dimensional structure of DNA, and over the next two decades, biologists and chemists worked to determine the mechanism of DNA replication. These scientists discovered restriction endonucleases, enzymes that splice DNA at specific sequences. In 1972, Paul Berg demonstrated the ability to use endonucleases to splice DNA at a specific site and then insert a segment of DNA from Simian virus.[12] This work led to the establishment of the first biotechnology company, Genentech, which was founded in 1976 by Herbert Boyer and Robert Swanson. Over the next three years, researchers at Genentech produced human somatostatin, human insulin, and human growth hormone in bacteria. The recombinant DNA methods the researchers used produced drugs at lower costs and larger quantities than previously possible.

As of May 2018, there were 2,910 biotechnology companies in the United States with a combined annual revenue of $109 billion.[13] Since the creation of Genentech, a close relationship has developed between university researchers and the biotechnology industry as both seek markets and applications for new discoveries and technology. Perhaps the biggest discovery in the past 20 years has been the Clustered Regularly Interspaced Short Palindromic Repeats-associated with protein-9 nuclease, commonly referred to as CRISPR-Cas9. Though first discovered by Francisco Mojica in 1993, it was the work of multiple researchers around the world that culminated in Feng Zheng's discovery at MIT that the same CRISPR-Cas9 complex could be used to target specific DNA sequences in both mice and humans.[14] *In vivo* experiments have demonstrated that this technology can be applied to living cells for the incorporation of foreign DNA into a host cell.[15] This inserted DNA sequence is then replicated and propagated into daughter cells during cellular replication. In short, the modified DNA is propagated into future generations of cells along with the effects of that modification. These genetic modifications can lead to a variety of outcomes such as production of a toxin (i.e., a protein), loss or

11 "Synthetic Biology Threat Agent Architecture," Department of Homeland Security, September 8, 2017, p. 4.

12 Simian virus, commonly abbreviated as SV40, is a DNA virus found in both monkeys and humans. The virus is a known oncogenic DNA virus. In African green monkeys, the virus causes cells to develop vacuoles and potentially develop into tumors. The virus gained notoriety when polio vaccine cultures were contaminated with the virus between 1955 and 1961, leading to increased cancer risk.

13 "Biotechnology—US Market Research Report," IBISWorld, May 2018.

14 Eric S. Lander, "The Heroes of CRISPR," *Cell* 164 (2016): pp. 18-28.

15 "CRISPR/Cas9 and Targeted Genome Editing: A New Era in Molecular Biology," New England BioLabs.

gain of cellular function (i.e., changes in a signaling pathway), and cell death.

Currently, an individual can purchase a CRISPR-Cas9 kit for a specific sequence for just a few hundred dollars. In 2017 alone, there were over 17,000 CRISPR-Cas9 studies published.[16] The exact cost varies depending on the length of the genetic sequence, but overall, the technology is relatively inexpensive. The genetic sequences for diseases such as smallpox, 1918 Spanish flu (H1N1), and anthrax have been published and stored openly in an online repository called GenBank.[17]

Simply possessing the genetic sequence does not, however, allow a nefarious actor to create a specific disease. *De novo* (starting without a complementary template) synthesis of DNA is difficult, requiring both specific equipment and laboratory skills. In 2017, it was announced that Canadian researcher David Evans at the University of Alberta had used "commercially available genetic material" and was able to *de novo* synthesize horsepox virus, a sequence of approximately 200,000 base pairs. This previously eradicated virus in North America is a cousin of smallpox virus and was synthesized for only $100,000, or approximately $0.50 per base pair.[18] Evans and his researchers purchased 30,000 base pair segments. The segments, which had overlapping sequences, were transfected, or inserted, into cells infected with Shope fibroma virus (a virus that causes cancers in rabbits), which annealed the segments together to create the full, viable horsepox virus.[19] The horsepox virus could then be isolated from the cells. The project took approximately six months to complete.

Virologist Gerd Setter stated, "If it's possible with horsepox, it's possible with smallpox."[20] In response to Dr. Evans' work, the World Health Organization Advisory Committee "acknowledged that, given the advent of synthetic biology it was no longer possible for society to entirely rid itself of the threat of smallpox or, indeed, other dangerous pathogens."[21] Dr. Evans and his team have not published, to date, a full accounting of their materials and methods used to create the horsepox. Dr. Evans is currently applying for a patent for his process and collaborating with Tonix Pharmaceuticals, which hopes to "use horsepox virus to develop a new vaccine for smallpox."[22] A researcher, graduate student, or even terrorist does not need *de novo* synthesis to create a specific DNA sequence; commercialization enables individuals to design and purchase a sequence. There are companies such as ATUM that can generate these sequences for insertion using the CRISPR-Cas9 complex. This does not mean companies blindly synthesize every order placed. In practice, every order is compared to the sequences on a pathogenic list. If the sequence matches one on the pathogen list, then the company has several options ranging from verifying the user, refusing to produce the sequence, and reporting the suspicious request to federal authorities.

Dr. Evans and his group were not, however, the first to recreate a virus *de novo*. Table 1 highlights previous work in the field dating back to 2002 with the re-creation of the poliovirus.

16 Julia Belluz and Umair Irfan, "2 new CRISPR tools overcome the scariest parts of gene editing," Vox, October 25, 2017.

17 Begona Aguado, Ian P. Selmes, and Geoffrey L. Smith, "Nucleotide sequence of 21.8 kbp of variola major virus strain Harvey and comparison with vaccinia virus," *Journal of General Virology* (1992): pp. 2,887-2,902; Christopher F. Basler et al., "Sequence of the 1918 pandemic influenza virus nonstructural gene (NS) segment, and characterization of recombinant viruses bearing the 1918 NS genes," Proceedings of the National Academy of Sciences, 2001, pp. 2,746-2,751; T. D. Read et al., "The genome sequence of *Bacillus anthracis* Ames and comparison to closely related bacteria," *Nature*, May 1, 2003, pp. 81-86.

18 Joel Achenbach and Lena Sun, "Scientists synthesize smallpox cousin in ominous breakthrough," *Washington Post*, July 7, 2017; Kai Kupferschmidt, "How Canadian researchers reconstituted an extinct poxvirus for $100,000 using mail-order DNA," *Science*, July 6, 2017.

19 "WHO Advisory Committee on Variola Virus Research, Report of the Eighteenth Meeting," World Health Organization, 2016, p. 29.

20 Kupferschmidt.

21 "Report of the Eighteenth Meeting," WHO Advisory Committee on Variola Virus Research, 2016, p. 30.

22 Achenbach and Sun.

Table 1: *Viruses that have been recreated* de novo.[23] *While some of the viruses listed are well known threats such as polio, Spanish influenza, severe acute respiratory syndrome (SARS), and West Nile virus, others appear innocuous and not commonly known. Bacteriophage ϕX174 has a relatively short genome and is frequently studied and used experimentally since it is known to hijack bacterial cells, inject its DNA, and force them to make new copies of the virus. The HERV-K (HLM2) is part of a family of human endogenous retroviruses that when overexpressed are a potential cause of amyotrophic lateral sclerosis (ALS) or lymphoma depending on the level of immune response. Simian immunodeficiency virus (SIVcpz) is a virus in chimpanzees that is analogous to HIV. The S13 bacteriophage, originally isolated from Salmonella, functions similarly to Bacteriophage ϕX174.*

Species	*Year*	*Citation*
Poliovirus	2002	Cello et al.[24]
Bacteriophage ϕX174	2003	Smith et al.[25]
1918 'Spanish' Influenza	2005	Tumpey et al.[26]
HERV-K(HLM2) (human endogenous retrovirus)	2006	Dewannieux et al.[27]
SIVcpz	2007	Takehisa et al.[28]
Bat SARS-like coronavirus	2008	Becker et al.[29]
West Nile Virus	2010	Orlinger et al.[30]
S13 bacteriophage	2012	Liu et al.[31]
Horsepox virus	2016	Kupferschmidt et al.[32]

The development of this technology does not directly equate to a terrorist's ability to use synthetic biology to create a biological weapon. A 2011 study entitled "Dual-Use Research and Technological Diffusion: Reconsidering the Bioterrorism Threat Spectrum" considers the expertise and equipment threshold required to execute different bioterrorism scenarios (Table 2).[33] These ranged from enhancing "the dissemination of a biological agent by contamination of food or water supplies late in a

23 "Synthetic Biology Threat Agent Architecture," p. 76.

24 Jeronimo Cello, Aniko V. Paul, and Eckard Wimmer, "Chemical synthesis of poliovirus cDNA: Generation of infectious virus in the absence of natural template," *Science* 297:5583 (2002): pp. 1,016-1,018.

25 Hamilton O. Smith, Clyde A. Hutchison, Cynthia Pfannkock, and J. Craig Venter, "Generating a synthetic genome by whole genome assembly: ΦX174 bacteriophage from synthetic oligonucleotides," *PNAS* 100:26 (2003): pp. 15,440-15,445.

26 Terrence M. Tumpey, Christopher F. Basler, Patricia V. Aguilar, and Alicia Hui Zeng, "Characterization of the reconstructed 1918 Spanish influenza pandemic virus," *Science* 310:5745 (2005): pp. 77-80.

27 Marie Dewannieux, Francis Harper, Aurélien Richaud, Claire Letzelter, David Ribet, Gérard Pierron, and Thierry Heidmann, "Identification of an infectious progenitor for the multiple copy HERV-K human endogenous retroelements," *Genome Research* 16:12 (2006): pp. 1,548-1,556.

28 Jun Takehisa et al., "Generation of infectious molecular clones of simian immunodeficiency virus from fecal consensus sequences of wild chimpanzees," *Journal of Virology* 81:14 (2007): pp. 7,463-7,475.

29 Michelle M. Becker et al., "Synthetic recombinant bat SARS-like coronavirus is infectious in cultured cells and in mice," *PNAS* 105:50 (2008): pp. 19,944-19,949.

30 Klaus K. Orlinger et al., "An inactivated West Nile Virus vaccine derived from a chemically synthesized cDNA system," *Vaccine* 28:19 (2010): pp. 3,318-3,324.

31 Yuchen Liu et al., "Whole-genome synthesis and characterization of viable S13-like bacteriophages," *PLoS One* 7:7 (2012): p. e41124.

32 Kupferschmidt.

33 Jonathan E. Suk, Anna Zmorzynska, Iris Hunger, Walter Biederbick, Julia Sasse, Heinrich Maidhof, and Jan C. Semenza, "Dual-Use Research and Technological Diffusion: Reconsidering the Bioterrorism Threat Spectrum," *PLOS – Pathogen*, January 13, 2011, pp. 1-3.

distribution chain" to "targeting materials to specific locations in the body."[34]

Table 2: Synthetic Biology Threat Level for Dual Use Research of Concern (reproduced from Suk et al.[35])

	Expertise Threshold Low (3), Medium (2), High (1)	**Equipment Threshold** Low (3), Medium (2), High (1)	**Threat Level**
Enhance the dissemination of a biological agent by contamination of food or water supplies late in a distribution chain	3	3	9
Increase the environmental stability of a biological agent by mechanical means (e.g., microencapsulation)	2	2	4
Confer resistance to therapeutically useful antibiotics or antiviral agents	2	2	4
Facilitate the production of biological agents	2	2	4
Enhance the dissemination of a biological agent by contamination of food or water supplies early in a distribution chain	3	1	3
Enhance the dissemination of a biological agent as powder or aerosol	1	2	2
Synthetic creation of viruses	2	1	2
Render a vaccine ineffective	1	1	1
Enhance the virulence of a biological agent	1	1	1
Increase the transmissibility of a biological agent	1	1	1
Enhance the infectivity of a biological agent	1	1	1
Alter the host range of a biological agent	1	1	1
Render a non-pathogenic biological agent virulent	1	1	1
Insertion of virulence factors	1	1	1
Enhance the resistance of a biological agent to host immunological defense	1	1	1
Insertion of host genes into a biological agent to alter the immune and neural response	1	1	1

34 Ibid., p. 2.

35 Ibid., pp. 1-3.

Generate a novel pathogen	1	1	1
Increase the environmental stability of a biological agent by genetic modification	1	1	1
Enable the evasion of diagnostic or detection modalities	1	1	1
Targeting materials to specific locations in the body	1	1	1

Calculated according to the formula total threat = (expertise threshold) x (equipment threshold), this table presents individual dual use research of concern (DURC) activities according to the ease with which a terrorist organization could be expected to replicate the work, based on expertise and equipment thresholds. The highest threat level comes from DURC activities that were deemed to require overcoming only low expertise and low equipment thresholds (such as contaminating a food or water source with an unaltered pathogen). Conversely, the lowest threat comes from highly sophisticated DURC activities that would need to overcome high equipment and expertise thresholds, such as those that would be required to substantially alter the genetic nature of a pathogen.

While many of the advanced bioterrorism scenarios in the study require high intellectual capacity and specific equipment, it does not account for the opening of community biology lab spaces, such as Genspace, where novice bio-enthusiasts can work with experts on a plethora of projects and equipment, or the International Genetically Engineered Machine (iGEM) competition. This competition for undergraduates focuses on developing novel products using synthetic biology.

Currently, synthetic biology researchers assess that graduate-level education in the field is required to manipulate genomes and create *de novo* genetic sequences. There are, however, developments that could reduce this education threshold especially as programs such as iGEM push this technology to younger populations.

The Do-It-Yourself (DIY) biology movement in conjunction with community lab spaces reduces the knowledge and infrastructure obstacles required to conduct most biological experiments. At Genspace, "for $100 per month, [you can] become a member and receive 24/7 access to Genspace's facility, equipment, and basic lab training from our staff. Work on anything biological as long as it meets our Biosafety Level 1 guidelines."[36] The Biosafety Level 1 restriction means the "microbes there are not known to consistently cause disease in healthy adults and present minimal potential hazard to laboratorians and the environment."[37] While restrictions on materials used in the lab exist, the techniques learned can be proliferated into a clandestine lab. Classes at Genspace include "DIY Fermentation," "Biohacker Bootcamp," "Genome Editing with CRISPR-Cas9," "2D DIY Bioprinting: Hack your home printer," and "DIYBIO Incubator: Build your own incubator."[38] There are currently over 40 community biology labs like Genspace, Baltimore Underground Science Space, BioCurious, and ChiTownBio to name a few in the United States alone.[39] Similar labs also exist in Europe, Asia, and South America.

36 Genspace website.

37 Biological Safety Levels (BSL) designate levels of containment for dangerous biological agents. As the BSL level increases from 1 to 4, so too does the required level of containment and precaution. BSL 1 is designated for "well-characterized" agents that are not known to consistently cause disease whereas BSL 4 is for "dangerous and exotic agents that pose a high individual risk of aerosol-transmitted laboratory infections and life-threatening disease that is frequently fatal." "Recognizing the Biosafety Levels," Centers for Disease Control and Prevention.

38 Genspace website.

39 "Local Groups," DIY BIO website.

Classes at community lab spaces do not overtly teach mechanisms for the development and delivery of biological weapons, but they do, however, provide a fundamental base of knowledge and techniques that could be applied to biological weapon development. These classes are akin to an undergraduate organic chemistry course; the knowledge is important for future chemists and doctors, however that same knowledge could be used to develop chemical weapons if applied in a nefarious manner. In addition to these DIY biology classes, many community labs in the United States require their members to participate in bio-ethics training. The presence of trained staff further reduces the risk of the lab equipment being used to develop a biological weapon.

New technologies have both reduced the cost of lab equipment and enabled individuals to build their own equipment using DIY techniques posted online. Currently, there are no government programs or professional standards to track discarded lab equipment such as incubators, polymerase chain reaction machines, and DNA sequencers. A new PacBio RS DNA sequencer, for example, costs approximately $700,000, which is likely too expensive for a terrorist attempting to establish a clandestine lab.[40] The growth of the DIY biology community, however, has created a market for used lab equipment. As lab equipment at universities and biotechnology companies is replaced, it is frequently resold. An older Perkin Elmer Prism 377 DNA sequencer costs $600 plus shipping and handling via eBay while on the same site a PCR thermocycler, which is used to make copies of DNA, only costs $150.[41] The cutting-edge technology being developed in today's labs will soon be replaced with even newer technology, and the former could likely end up for sale online.

While some equipment must be purchased, other equipment can be made cheaply and clandestinely. Websites such as DIY-BIO provide instructions for biology enthusiasts to make their own lab equipment. The website provides building instructions for such items as a PCR machine, microcentrifuge, and a gene gun, which is a device used to inject foreign DNA coated with a heavy metal into a target cell.[42] There are several websites that provide "hacks" for making this lab equipment out of materials accessible at hardware stores, including light bulbs, drills, and piping.

Synthetic biology is lowering the technical threshold, in terms of both knowledge and skill, required to modify genetic material. This technology is widening the scientific aperture to enable those who are not trained and educated in molecular biology, microbiology, biochemistry, and other fields to experiment with DNA and modify organisms.

Additive Manufacturing

Additive manufacturing (AM), which is commonly referred to as 3D printing, made headlines in recent years after Cody Wilson published his "Liberator" design, a 3D-printed gun.[43] Additive manufacturing is not quite, however, a new technology. The first commercial AM machine, SLA-1, emerged in 1987 using a technique called stereolithography, which uses an ultraviolet laser to solidify thin layers of a light-sensitive polymer.[44] This method is referred to as VAT photo-polymerization since the liquid photo polymer generally resides in a large tank, or vat. Currently, there are six additional AM techniques: material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and direct energy deposition. Figure 1 illustrates all seven additive manufacturing techniques.

Material jetting is akin to the process undertaken by an ink jet printer and utilizes either continuous

40 "Price and Sequencing Capability Comparison of PacBio RS, Ion Torrent PGM, and Illumina MiSeq," Next Gen Seek website.

41 "Lot of 2 Perkin Elmer ABI Prism 377 DNA sequencer / genetic analyzer," eBay, accessed on October 8, 2017; "MJ Research PTC-100 Programmable Thermal Cycler," eBay, accessed on May 31, 2018.

42 "DIYbio Lab Equipment," DIY BIO website.

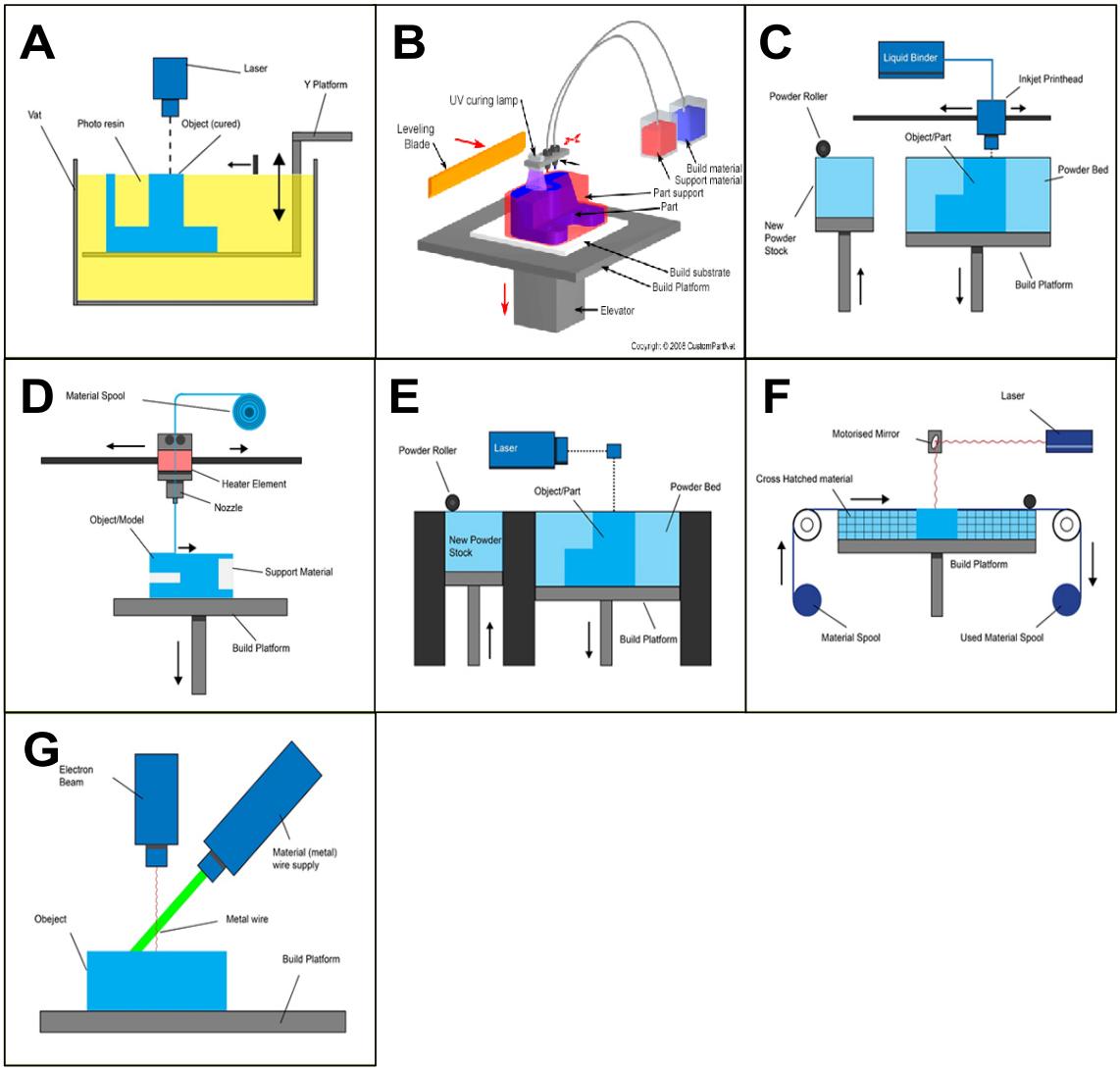
43 "Evolution of 3D Printing Technology Raises Security Concerns," INFOSEC Institute.

44 Terry Wohlers and Tim Gornet, "History of additive manufacturing," *Wohlers Report*, 2014, p. 1.

stream or drop-on-demand. The possible materials made from this process are limited to specific designs and strength since the jetting processes uses droplets, consequently limiting the types of polymers' viscosity and ability to form droplets.

The binder jetting process uses two building materials: an adhesive binder and powder build material. These machines deposit material on orthogonal planes. After deposit of one layer, the object is lowered for the next layer to be added. Because of this binding process, "the material characteristics are not always suitable for structural parts and despite the relative speed of printing, additional post processing can add significant time to the overall process."[45]

Figure 1: Schematics of the seven additive manufacturing techniques: (A) VAT polymerization, (B) material jetting, (C) binder jetting, (D) material extrusion, (E) powder bed fusion, (F) sheet lamination, and (G) directed energy deposition[46]



Material extrusion heats a material as it passes through a nozzle and then deposits it layer by layer. For this process, several variables must be controlled. For example, the material passed through the nozzle

45 "About Additive Manufacturing: Binder Jetting," Additive Manufacturing Research Group, Loughborough University.

46 "About Additive Manufacturing," Additive Manufacturing Research Group, Loughborough University.

needs to be kept under pressure and passed through at a constant rate. (Failure to adequately control pressure and flow rate leads to variable layer thickness.) The layers are bonded via either temperature control or the addition of a chemical agent.

The powder bed fusion process can use almost any powder-based materials as well as some metals such as stainless steel, titanium, aluminum, and cobalt chrome. This process uses a roller to spread a layer of material approximately 0.1mm thick onto a build platform. The material is then heated, fusing the material together using a laser, electron beam, or direct metal laser sintering, just to name a few. This process repeats until the model is created. The heating process dictates the type of material used.

The sheet lamination processes use either sheets or ribbons of metal or paper depending on the process. The material is positioned on a cutting bed and bonded in place over the previous material. The excess material is then cut using either a laser or a knife. This process repeats until the model is complete. The greatest limitation of this process is the type of material, currently on plastics and polymers, that can be used.

Directed energy deposition uses a laser or electron beam to melt material onto a specified surface. The material is deposited from a multi-axis arm, allowing the material to be deposited from any desired angle. This process typically uses polymers or ceramics but can use metal from a thin wire. This process sacrifices speed for accuracy and is commonly used to repair pre-existing materials.

The applications of additive manufacturing are far reaching. The U.S. military, for example, currently requires a multitude of products and materials for its various pieces of vehicles, weapons, and clothing. Several branches of the military are examining how incorporation of multiple printing techniques could reduce the necessity to maintain a large inventory of replacement parts from multiple vendors. One constraint of this application is that many components consist of multiple materials such as metal, plastic, and electronics all on a single component. Consequently, multiple printing techniques are required and "companies (Autodesk's Project for Echer Software) are already developing advanced 3D printing and manufacturing systems that are capable of using multiple processes and toolsets at the same time to build and assemble complete, working electronic devices."[47] According to 3Dprint.com, "The Air Force is already exploring how bringing advanced metal 3D printers into their maintenance centers to print replacement parts as needed rather than maintaining huge inventories of parts and components can change the entire fleet management workflow."[48]

For large objects, time is currently the most significant constraint. With AM, accuracy and quality come at the expense of speed. In an experiment for Forbes, it was possible to print a copy of Cody Wilson's "Liberator" pistol in 48 hours for $25 worth of plastic using a non-commercial grade 3D printer (Lulzbot A0-101) in 2013.[49] This gun fired nine shots before breaking. Additive manufacturing machines have evolved and are capable of printing more complex items in less time with greater resolution. For example, Eric Harrell printed a functioning General Motors LS3 V8 engine in 200 hours using over two kilograms of filament.[50] While Harrell demonstrated his printed engine functions, it was not tested in an operational environment under the standard stress and heat of normal engine operation.

In May 2018, NASA announced the development and patenting of a new additive manufacturing method called laser wire direct closeout. LWDC is analogous to the direct energy deposition method. Using this similar technique, NASA has begun testing a new nozzle for which the "hot wall of the nozzle is only the thickness of a few sheets of paper and must withstand high temperatures and strains

47 Scott Grunewald, "The Surprising Ways That 3D Printing May Completely Transform the US military," 3Dprint.com, April 9, 2016.

48 Ibid.

49 Andy Greenberg, "$25 Gun Created With Cheap 3D Printer Fires Nine Shots," *Forbes*, May 20, 2013.

50 Kristen Lee, "This Fully Working 3D Printed Chevrolet LS3 V8 Is The Coolest Thing," Jalopnik, January 3, 2017.

during operation."[51] Their tests have currently run the nozzle for 1,040 seconds at high combustion and pressure.

While the physical constraints of 3D printing continue to decrease, the process is still dependent on the computer-aided design (CAD) files that provide the specific computer control information for a printer to create a specific object. Essentially, the CAD files are the procedures for a printer to make a designated object. The democratization of this technology has encouraged users to share their CAD files and knowledge across multiple forums on the internet. While it is necessary to have a CAD file to 3D print, these files can easily be generated from 3D scanners.

Additive manufacturing is not limited to just plastic and metal objects. The growing field of 3D bio-printing, which uses the fundamental principles of standard additive manufacturing, is enabling researchers to develop organ-like structures *in situ* and potentially fully functioning organs. CELLINK, for example, has developed the BIO X 3D printer, which the company hopes will be able to print fully functioning organs. No two organs are alike, and 3D bio printing is incorporating both static and moving components. Erik Gatenholm, the CELLINK CEO, states, "a bone ink has a different composition and behaves differently because the bone cells need to thrive in that environment, versus, for instance, an ink for the heart because the heart tissue needs [to be] softer and needs to be somewhat elastic."[52] The machines created by CELLINK use living cells and range in price from $9 to $300.

In the near future, it is likely that 3D bio printing will be coupled with cell-free synthetic biology to create platforms to easily "synthesize complex proteins, toxic proteins, membrane proteins, and novel proteins with unnatural amino acids."[53] While this extract-based system will increase research capabilities, the ability to express toxic proteins such as ricin pose a potential threat. These systems are currently small and produce limited quantities of proteins and metabolites for studies due to the practical challenges of separation/product purification, but as these techniques improve, so will cell-free production.

The benefits of additive manufacturing and its corresponding commercialization will cause the technologies to advance rapidly. According to the U.S. Department of the Army's Emerging Science and Technology Trends: 2016 – 2045 report, "By 2040, 3D printers will be able to print objects that incorporate multiple materials, electronics, batteries, and other components. People will be able to print tools, electronics, replacement parts, medical devices, and other products on demand, customized to their wants and needs. Military logistics will likely become streamlined, as equipment and supplies will be printed directly at their point of use. Objects will become information, and digital piracy will replace shoplifting. Terrorists and criminal organizations will print weapons, sensors, and other equipment using raw materials that will be almost impossible to track."[54]

Unmanned Aerial Systems/Vehicle (UAS/UAV)

The commercialization of unmanned aerial systems, commonly referred to as drones, has led to the development of small, nimble fixed-wing and quadcopter UAVs capable of carrying payloads for a variety of purposes. The use of drones to target individuals first became prevalent in the post-9/11 period, with the United States first using armed drones in late 2001 during the early stages of the war in Afghanistan. But use of armed drones only moved into public prominence in the latter half of that decade as U.S. drone strikes in Pakistan and elsewhere increased dramatically and became public knowledge. This period was not the first use of armed drones, however.

51 Jennifer Stanfield, "NASA Marshall Advances 3-D printed Rocket Engine Nozzle Technology," NASA, May 19, 2018.

52 Bruce Gellerman, "How 3D Bioprinting Could Revolutionize Organ Replacement," wbur.org, November 22, 2017.

53 Yuan Lu, "Cell-free synthetic biology: Engineering in an open world," *Synthetic and Systems Biotechnology* 2:1 (2017): pp. 23-27.

54 "Emerging Science and Technology Trends: 2016 – 2045," Office of the Deputy Assistant Secretary of the Army (Research and Technology), April 2016, p. 3.

During World War I, the Navy worked on developing "air torpedoes," using unmanned Curtis biplanes launched from a catapult. The planes were "pre-programmed" to reach a specified altitude and distance before diving toward the ground. This program, which was run out of a small airfield on Long Island, New York, died out in 1918 with the end of World War I.[55]

World War II saw renewed interest in drone technology on both the Allied and Axis sides. The German V-1 was launched toward London from the French coast only a week after the D-Day invasion with the promise of more weapons such as the V-2. Within the United States, the Army, Air Force, and Navy all had drone programs at the time—Aphrodite and Anvil, respectively.[56] The Navy's Operation Anvil focused on full-scale target drones that were used prior to the war for target practice, while the Army's program focused on small, low-cost systems. To counter the V-1 threat, both the Army and Navy sought to incorporate televisions developed by RCA along with radio control technology. Ultimately, a human crew would take the airplane to a cruising altitude and engage the autopilot before ejecting. The plane was then controlled remotely from a nearby control plane. Despite efforts, these programs were not very successful at destroying the V-1 facilities.

As technology continued to advance, so too did the ability to remotely and accurately control the unmanned aerial vehicle. In Vietnam, the Navy's Firebee AQM-34, which had previously been used for aerial gunnery, was used in an intelligence collection role.[57] Drones were later used by Israel as decoys in the Bekaa Valley during the 1982 Lebanon War.[58] The United States, through the development of the Predator drone and its successors, continued to use drones for surveillance and ultimately armed the unmanned vehicle with the Hellfire missile. The use of armed drones quickly proliferated.

In 2002, the U.S. Department of Defense reportedly had 167 drones in its inventory, and as of 2015, there were over 8,000.[59] The United States is not the only country that has used armed drones in conflict. According to a New America study, eight other countries have used armed drones in conflict: Israel, the United Kingdom, Pakistan, Iraq, Nigeria, Iran, Turkey, and Azerbaijan. Other countries are also seeking to add armed drones to their inventory. Currently, 39 nations possess armed drones.[60]

Over the past few decades, drone technology has proliferated beyond nation-states and into both the private sector and ultimately terrorist organizations. The first known terror group's interest in drones was Aum Shinrikyo in late 1993.[61] Another example occurred in 2004 when Hezbollah launched a surveillance drone into Israeli airspace that hovered over Western Galilee before returning.[62] A little over a decade later in October 2016, Kurdish forces shot down and captured an Islamic State quadcopter that had been armed with explosives.[63]

The list of non-state actors that possess UAS capability has grown robust, including Houthi rebels in Yemen, Hamas, Lashkar-e-Taiba, the Revolutionary Armed Forces of Columbia (FARC), and the Haqqani network to name just a few.[64] The drones used by both Hezbollah and the Islamic State are not the same as those used by nation-states; rather these are smaller, hobbyist drones that are

55 Ibid.

56 Roger Connor, "Remembering the Death of Lt. Joe Kennedy Jr. and America's First Combat Drones," Smithsonian National Air and Space Museum, August 19, 2014.

57 Clinton Fernandes, "Welcome to the Future: The Use of Drones in War," *Dissent Magazine*, Summer 2012/2013.

58 Uri Sadot, "Proliferated Drones: A Perspective on Israel," Center for New American Studies, May 2016.

59 Ibid.

60 Peter Bergen, Melissa Salyk-Virk, and David Sterman, "World of Drones," New America Organization.

61 Don Rassler, *Remotely Piloted Innovation: Terrorism, Drones and Supportive Technology* (West Point, NY: Combating Terrorism Center, 2016).

62 Ibid., p. 61.

63 Bergen, Salyk-Virk, and Sterman.

64 Rassler.

commercially available. The FAA estimates that by 2020, there will be seven million drones in the United States alone, of which 4.3 million will be hobbyist drones while the remaining 2.7 million will be commercial vehicles.[65]

Commercially available drones have diverse capabilities ranging from the delivery of packages, video/photography, and industrial usage at a relatively low cost. The AGRAS MG-1S made by DJI, for example, is capable of carrying a 10-kilogram fluid payload to assist in the delivery of pesticides and herbicides.[66] With these capabilities, the applications of a UAS by a terrorist is up to the creativity of the enemy.

Current UAS, whether gas or battery powered, are limited by their energy capacity. Most hobbyist quadcopters use batteries, reducing the noise on the craft since no combustion engine is required. Most hobbyist drones are limited to approximately 30 minutes of flight, constraining the distance a UAS can travel. Commercialization of these drones is pushing research to produce batteries that are more efficient and light-weight and have increased storage capacity.

There is also ongoing research to develop autonomous drones. Using machine learning and image recognition, these drones are able to avoid obstacles, such as powerlines, and deliver their payload on a target. This software component would enable drones to be used in swarms, where multiple drones are controlled with minimal input from a single user. This software technology is being developed by academics, private industry, government entities, and defense contractors, but is not currently available with commercial drones. However, in the next five to 10 years, it is likely that a large number of autonomous drones will be available and flying.

One concern about drones is their potential to take down commercial aircraft. The Alliance for System Safety of UAS through Research Excellence (ASSURE) released a study in 2017 examining the potential damage of a 2.7-pound quadcopter, a 4-pound quadcopter, a 4-pound fixed wing UAV, and an 8-pound fixed wing UAV in this regard. The study used characteristics of a Boeing B737 and Airbus A320, which represents 70 percent of the commercial aircraft fleet, and the Learjet 30/40/50 business jet. The study noted that "commercial aircraft manufacturers design aircraft structural components to withstand bird strikes from birds up to eight pounds for the empennage and four pounds for windscreen. ASSURE simulations show small UAV collisions inflict more physical damage than that of an equivalent size and speed bird-strike. Small UAV components are much stiffer than birds, which are mostly composed of water. Therefore, bird-strike certification regulations are not appropriate for unmanned aircraft."[67] It should be noted that it was a bird strike that forced U.S. Airways flight 1549 to lose engine power and ditch on the Hudson River in January 2009.

As commercialization drives improvements in flight duration, payload capacity, and flight software, the risk of a UAS being used to deliver a WMD increases. DJI's AGRAS MG-1 has the dual-use capability to deliver a chemical weapon agent now. The DJI website claims it can cover 4,000-6,000 m^2 in approximately 10 minutes; an American football field is 5,360 m^2.[68] This is just one possible nefarious use of current UAS technology, but as payload capability increases, the capacity to deliver a radiological dispersion device becomes a more distinct possibility. The delivery of biological weapons agents or a nuclear weapon remains highly problematic, however, due to strain on the bio-agent and the weight of a nuclear device.

65 Mark Pomerleau, "FAA estimates 7 million drones by 2020," GCN, March 28, 2017.

66 "AGRAS MG-1S," DJI Enterprise, DJI website.

67 "FAA and ASSURE Announce Results of the Air-to-Air Collision Study," ASSURE, November 28, 2017.

68 "AGRAS MS-1S."

The Nexus of Emerging Technologies with WMD Terrorism

Having established baseline context on the history and evolution of these three technologies, this report will now focus on the threat nexus, and discuss how these technological developments might enable WMD attacks by terrorists. It will examine, in turn, the threat of terrorist development of nuclear, chemical, and biological weapons. For each, this section will assess the impact and applicability of these three emerging technologies on the weapon category in question.

Nuclear

Nuclear weapons remain and will continue to remain the most difficult weapon of mass destruction to develop and employ, not only for a terrorist but also a nation-state. There are a multitude of technical and material hurdles that must be overcome in order to develop a nuclear weapon, the largest being the acquisition of fissile material, which is an atom that splits upon capture of a low-energy neutron. This process releases a considerable amount of energy. (The exact amount depends on which atom is split.) There are two fissile materials: Uranium-235 and Plutonium-239. Collectively, these are commonly referred to as special nuclear material.

Uranium. Uranium, though rather abundant, exists primarily in two isotopes, 235 and 238. Isotopes are atoms that have the same number of protons and electrons but differ in the number of neutrons in the nucleus. Uranium-238 (U-238) and Uranium-235 (U-235) both have 92 protons and electrons, while differing by three neutrons—146 and 143, respectively. Unenriched, or natural, uranium is mostly U-238, and it constitutes approximately 99.3 percent of all uranium ore. Uranium-238, however, is not fissile, meaning it does not propagate neutron emissions. Consequently, the two isotopes need to be separated—a process called enrichment—in order to possess a significant quantity, which is the amount of material (Table 3) required to make one nuclear weapon, of U-235. According to the International Atomic Energy Commission, this quantity is approximately 25kg of U-235.[69] The process of enrichment is extremely difficult and requires tremendous resources of money, space, energy, and materials.

Table 3: Significant Quantities of Fissile Material[70]

Material	*Significant Quantity*
Plutonium-239	8 kg
Uranium-233	8 kg
Highly Enriched Uranium (U235 > 20%)	25 kg

There are several uranium enrichment methods used worldwide: gaseous diffusion, gaseous centrifuge, and laser separation. These processes, however, first require the conversion of uranium ore in which the uranium exists as triuranium octoxide (U_3O_8) into uranium hexafluoride (UF_6). The exact chemical method depends on the origin of the ore since other metals present can affect the chemistry.

Once converted, in the gaseous diffusion process, the UF_6 is pushed under pressure through porous membranes selective to the UF_6 molecules. This process takes hundreds of membranes, but since U-235 has a slightly smaller mass than U-238, the UF_6 with the U-235 isotope separate further to

69 "IAEA Safeguards Glossary," International Atomic Energy Commission, 2001 Edition, p. 23.

70 Ibid. Uranium-233, similar to Plutonium, is not naturally occurring; rather it is produced in the Thorium fuel cycle when Th-232 absorbs a neutron to become Th-233. The Th-233 isotope has a half-life of 22 minutes before decaying to Protactinum-233, which has a half-life of 27 days before decaying to Uranium-233 (U-233). The Thorium fuel cycle was explored to avoid the production of plutonium and to address the proliferation concerns with this material. The United States first tested a weapon with U-233 in April 1955 during Operation Teapot.

the low-pressure area.[71] This process requires a large amount of energy to maintain the appropriate pressures, and the membranes need to be changed regularly since UF_6 is corrosive.

The gas centrifuge process uses a large number of rotating cylinders in both series and parallel to separate the U-235 and U-238 isotopes in the UF_6. These centrifuges spin at several thousand rotations per second; the exact speeds depend on the models of the centrifuges (height and width) as well as the design of the cascade. Higher speeds equate to faster separation. The U-235, once again, is lighter than the U-238 isotope and separates out.[72] A single pass through a centrifuge is not enough to separate the isotopes required to achieve reactor-grade uranium, let alone weapons-grade. The process generally uses the principle of quantity over quality; consequently, most gas centrifuge facilities consist of hundreds to thousands of centrifuges. This process once again requires a substantial amount of energy, and the centrifuges are prone to breaking as a result of spinning at high speed.

Gas centrifuges have been made out of carbon fiber composite, aluminum, and maraging (or strengthened) steel. It is possible to 3D print carbon fiber, so it is possible that a gas centrifuge could be 3D printed.[73] There are several limitations, however. First, it takes several hundred to several thousand centrifuges to produce a significant quantity of Uranium-235.[74] Subsequently, the process of making centrifuges alone would be extremely time and material consuming. Secondly, the spinning of UF_6 as a gas exerts tremendous forces on the sides of the centrifuge. And while it is possible to spin that UF_6 gas at sub-optimal speeds, this only further increases the time required to produce a significant quantity.

From an additive manufacturing perspective, the carbon fiber would need to be extruded in a continuous manner and annealed to the previous layer. A 3D-printed tube using continuous extrusion would also require significant post processing to smooth edges and potential imperfections along the interior surface. Imperfections would disrupt the ideally uniform countercurrent flow used to separate the isotopes as well as create hotspots where the atoms would interact with metal, increasing the heat at those locations. Post-production processing adds time and makes centrifuge production, though possible, impractical. Additive manufacturing, however, would be one method to avoid export controls currently associated with centrifuge technology.

As previously mentioned, there is an opportunity to use a 3D scanner of a centrifuge to generate the necessary CAD file. Resolution from the scanner, however, is an issue. Variations of 0.5mm in a CAD file for a gas centrifuge for uranium separation, for example, could easily change the precise harmonics required to separate uranium isotopes at high speeds. The harmonics of the gas centrifuge refers to the vibrations in the centrifuge created as the uranium hexafluoride is spun at increasing speed. It is possible to separate below the first harmonic, depending on design, however it greatly reduces the separation efficiency.

Laser separation is a new method that excites the isotopes of uranium using a laser. The three-neutron difference causes the isotopes to excite slightly differently; specifically changing its chemical properties and allowing separation. This system requires three major components: the laser, the optical system, and the separation module. The Separation of Isotopes by Laser Excitation (SILEX) uses UF_6 while the method developed by the U.S. Department of Energy uses a metal alloy.[75]

So to summarize the applicability to uranium enrichment of the three emerging technologies discussed in this report, AM could be used to assist in the gaseous centrifuge process, although its use would still pose some significant challenges and would not be the optimum or most efficient method

71 "Uranium Enrichment," United States Nuclear Regulatory Commission.

72 Ibid.

73 Companies such as Markforged have commercially available 3D printers capable of printing carbon fiber composites.

74 The exact number of centrifuges depends on the separative work units, commonly referred to as SWUs, of the machine. The SWUs are dependent on the design of the centrifuge since the height and diameter of the machine can vary.

75 "Uranium Enrichment."

to accomplish this step. These particular technologies would not assist with gaseous diffusion or laser separation.

Plutonium. While uranium can be mined and then enriched through physical and chemical processes, plutonium does not naturally exist. Plutonium must be created and then chemically separated. This element is only created in a nuclear reaction when a U-238 atom absorbs a neutron and transmutes to plutonium. Uranium used in most energy reactors is lightly enriched, meaning only three to five percent U-235 in the fuel rods. There are reactors that produce isotopes used for medical treatment, and their enrichment is higher at nearly 20 percent U-235. Consequently, the bulk of this uranium is U-238, which can produce plutonium.

There are several isotopes of plutonium created in this reaction, but only Pu-239 and Pu-241 are fissile. The amounts of the isotopes vary depending on the burn, or how long the uranium is consumed in a nuclear reaction, and the number of neutrons in the reaction. The burn rate of the uranium is dependent on several factors, including the reactor core configuration, the exact ratio of U-235 to U-238 in each fuel rod, and the amount of neutron absorbers in the core. An absorber is a material that slows a fast neutron (2 MeV) to a thermal neutron (1 eV) so that it can be absorbed by the nucleus of an atom instead of deflected.

Nuclear reactors are designed to prevent access to the fuel rods while the reactor is operational, with the exception of the early Magnesium oxide (MAGNOX) reactor design. The MAGNOX reactor uses natural uranium in its fuel rods, reducing their production costs, which is particularly ideal for developing nations to provide power to its citizens. The reactor is cooled by carbon dioxide and uses graphite as a moderator, which is a material that absorbs neutrons without undergoing fission. The early designs enabled nuclear plants to change out fuel rods without taking the reactor off-line, which would otherwise be a signature, from a proliferation stand point, that the fuel rods are being accessed. It was this type of reactor that Pakistani scientist A.Q. Khan stole the plans for and sold to Iran. A.Q. Khan also provided these plans to North Korea in exchange for Nodong missiles.[76] Since then, the United Kingdom has modified its MAGNOX reactor to prevent removal of the fuel rods, however, the design had already been proliferated to two rogue states with nuclear ambitions.

The decay half-life of Pu-241 is approximately 14.4 years. As it decays to Americium-241, the energy given off is absorbed by the surrounding material as heat. This heat can destroy the nuclear material, especially since a specific lattice geometry and density of the metal is required. Consequently, the plutonium isotopes need to be chemically separated to have enough Pu-239 for a fissile reaction while minimizing the amount of Pu-241 so that the natural decay does not destroy the significant quantity of fissile material. This is critical when the metal undergoes compression with high explosives, and defects in the pit could cause the device to fizzle.

The separation of plutonium from uranium in a spent nuclear fuel rod requires specific equipment and a knowledge of chemistry, but this knowledge requirement is not insurmountable for a terrorist organization. The acquisition and handling of the spent fuel rods—which are not only hot from the radioactive decay, but also emit deadly amounts of ionizing radiation—is a limiting factor preventing a non-state actor from reprocessing to extract plutonium.

While the acquisition and handling of spent fuel rods is a significant limiting factor preventing a non-state actor from reprocessing to extract plutonium, the equipment needed for the actual extraction can be found in any chemical engineering lab at most universities in the United States. The process requires large quantities of nitric acid and tributyl phosphate, which are used in many industries around the world. The separation is made possible due to the preferred oxidation states of plutonium and uranium and the preference of molecules in these oxidation states to dissolve in the solvent while other decay products are separated out. The specific knowledge of actinide chemistry is critical for the

76 David Lowry, "The UK's role in nuclear proliferation: then and now," Nuclear Monitor 767 (2013).

extraction process. Otherwise, the plutonium is not extracted or there are too many decay products in the final extract. The heat given off from the decay products makes the crystallization process of the plutonium difficult at best.

While additive manufacturing and unmanned aerial systems do not seem applicable to plutonium extraction, there is the potential to use synthetic biology. At first glance, synthetic biology does not appear to have a place in the development of nuclear weapons. However, the reduction-oxidation (redox) reactions of a cell's biochemical pathway are analogous to the redox reactions involved in plutonium extraction. Synthetic biology, as previously discussed, is the rational design and construction of modified or new biological systems/organisms with desired functionality. This includes biochemical pathways. The methods of synthetic biology that seek cures for the diseases of biochemical pathways, such as Porphyria, can also be applied to create proteins that have an affinity for the oxidation states of plutonium.[77] Microbes were used in 2010 to help clean the Deepwater Horizon oil spill, so theoretically these microbes could be modified to selectively scavenge plutonium.[78]

This process is not simple, and there is a necessary level of knowledge and laboratory equipment required. In the next five to 10 years, however, commercialization will make this process accessible to a greater population. At the current rate of commercialization, a patient terrorist with a moderate knowledge of biochemistry and synthetic biology would be able to modify organisms to select for plutonium, eliminating much of the reprocessing signature.

While acquisition of a significant quantity of special nuclear material is the largest hurdle, it is not the *only* hurdle. This material must then be incorporated into a functioning weapon. There are two basic designs for nuclear weapons: gun-type device, similar to Little Boy, which was used during World War II on Hiroshima, and an implosion device, like Fat Man, which was used on Nagasaki. A gun-type device is the less complex of the two and uses explosives to unite one section of U-235 into another. The velocity provided to the uranium is essential in order for two sections to meet and become critical. If the speed is too low, then the device will fizzle and not achieve a nuclear detonation.

An implosion device compresses a core of plutonium using conventional high explosives. The core is designed to be non-critical; however, once compressed, the configuration of the core changes. The distance between plutonium atoms is reduced and enough material is present for a nuclear chain reaction to continue by itself as neutrons are emitted and absorbed. This configuration is commonly referred to as criticality, which leads to a nuclear detonation. This design is more complex due to the necessity for uniform compression around the core. Consequently, the triggers and explosives need to be manufactured to provide nanosecond accuracy. Such triggers and explosives are difficult to acquire. Failure to achieve uniform compression causes the core to split and blow apart without achieving a nuclear detonation.

Assuming a terrorist organization is able to overcome the most significant hurdle and acquire significant quantities of special nuclear material for a nuclear weapon, both additive manufacturing and unmanned aerial systems could potentially help transform the material into a weapon. Recent work at Los Alamos National Laboratory and Purdue University has demonstrated that explosives could be made using additive manufacturing. The advantage of 3D printing is that the explosives could be printed into the necessary shapes to achieve an implosion or propel a slug of uranium. This process, however, is not perfect. Small bubbles and imperfections could arise in the explosives from this process if the terrorists were impatient and steps were not implemented to ensure quality control. In order for a terrorist to truly achieve a nuclear detonation, they would need to conduct a series of tests prior to

77 Porphyria is a metabolic disorder in which one of the eight steps required to properly form the iron complex that carries oxygen does not occur correctly. This leads to the accumulation of porphyrins or their precursors molecules, which ultimately affect the skin and nervous system of the individual. Those suffering from the disorder often get blisters and scarring on the skin when exposed to sunlight.

78 David Biello, "Clean Up the Deepwater Horizon Oil Spill," *Scientific American*, May 25, 2010.

the employment of a weapon. Imprecise explosives surrounding special nuclear material would simply cause its dispersion as a radiological dispersal device (RDD).

The relevancy of UAS comes in its potential use as a delivery system for the weapon. Current commercial UAS are typically limited to an approximately 10kg capacity. Consequently, these models would not be able to carry the required 25kg of highly enriched uranium, however they could lift the 8kg of plutonium. With the mass of the explosives and triggers added, however, current UAS models would not be able to deliver a nuclear weapon to a target. But commercialization and use in industry is pushing for greater payload capacity, and within the next five to 10 years, it is likely that a quadcopter-style UAS will be able to carry the mass of a nuclear weapon.

The path toward possessing a nuclear weapon by a state, let alone a terrorist or terrorist organization, is arduous at best. Despite the potential for the three technologies discussed in this report to enable the development of a nuclear weapon in the future, the risk remains low. The patience and capabilities required to develop a clandestine nuclear weapon using these technologies is significant, and development requires both a high level of education and assets that are potentially traceable.

Chemical

Chemical weapons remain the easiest weapon of mass destruction for development and employment by terrorist organizations. The hurdles, in terms of specific equipment and knowledge required to develop a chemical weapon agent, are easier to overcome than with other WMD, and these weapons have been used on numerous occasions. Simplistic equipment can be purchased at a hardware store and much of the technical knowledge can be found on the internet, in open patents, or in chemical literature, including data on reaction kinetics, catalysts, and operating parameters.[79]

Chemical weapons agents exist across a spectrum of quality, ranging from military grade, which requires small quantities to be lethal and degrades slowly overtime, to homemade, which requires large quantities to be effective and degrades rapidly. The effectiveness of chemical weapons agents is impacted by a multitude of environmental factors such as temperature, humidity, wind speed, and sunlight. Aum Shinrikyo in Japan and the Islamic State in far more austere conditions have demonstrated this fact. For example, sulfur mustard has a higher boiling point (217°C) and lower vapor pressure (0.11mm Hg at 25°C) than sarin (147°C and 2.9mm Hg at 25°C, respectively).[80] These physical properties suggest that sulfur mustard should be more persistent, however the deployment of sarin by Aum Shinrikyo in an enclosed, temperature-controlled subway car without explosives allowed the sarin to persist longer, potentially affecting more individuals. The high temperatures and low humidity of the Iraq/Syrian environment coupled with the use of explosives by the Islamic State to disperse the sulfur mustard would cause the agent to evaporate faster. Aum Shinrikyo's technical base was also much greater than the Islamic State's, and the former group had access to more sophisticated equipment, making it likely that the agent Aum Shinrikyo employed contained less impurities.

The precursor chemicals required to make these agents are widely available. For example, the predominant precursor for sulfur mustard gas is thiodiglycol. This chemical is used in a variety of products including pen inks, plastics, lubricant additives, antifreeze, and photogenic developing solutions. This precursor is just one chemical reaction away from conversion to sulfur mustard using a chlorinating agent such as hydrochloric acid, which is also readily available. As one study found, "This process does not require a particularly sophisticated chemical industry; indeed, it could be performed in a basement

79 Randall Forsberg, William Driscoll, Gregory Webb, and Jonathan Dean, *Nonproliferation Primer* (Cambridge, Massachusetts: MIT Press, 1999), p. 50.

80 "Mustard Agents," OPCW website; "Nerve Agents," OPCW website.

laboratory with the necessary safety precautions."[81] And a terrorist organization will likely not require the same level of safety precautions as a state actor.

In 2001, Dr. James M. Tour and, independently, George Musser of *Scientific American* ordered and received the precursors to make several chemical weapon agents, including VX, Soman, and Cyclosarin (GF). These supplies cost approximately $130 and could make up to 280 grams of the agent.[82] The lethal dose for 50 percent (LD50) of a population for VX through dermal absorption is 0.04 micro-gram per kilogram (μg/kg).[83] A 200-pound person weighs approximately 90 kilograms, which is an LD50 of 3.6 μg/person. The 280 grams that could be produced would be enough to kill approximately 77 million people at the LD50, if untreated.[84] This estimation, however, assumes no material is lost in the dissemination process (i.e., every drop of the chemical agent is absorbed through the skin) and there is no contamination that would degrade the chemical agent.

Dr. Tour is an accomplished biochemist with access to state-of-the-art laboratory equipment and facilities. A "sophisticated production facility" to make military significant quantities of one type of nerve agent might cost $30-50 million.[85] Terrorists, however, do not require "a sophisticated production facility" to produce chemical weapons, as demonstrated by the Islamic State. A terrorist organization could use batch processing to make small yet effective quantities of a chemical agent.

Chemical weapons agent decomposition is dependent on environmental factors such as temperature, humidity, sunlight exposure, and wind speed. Sulfur mustard, for example, has a half-life of 24 minutes at room temperature in physiological solutions since it reacts with water to revert to its precursors thiodigycol and hydrochloric acid.[86] Higher temperatures and increased humidity would decrease this half-life time, increasing the rate of decomposition.

Impurities in the chemical weapon agent also further decrease the agent's survivability. These impurities can be introduced during the production process. Incomplete reactions leave reactants in the final agent while unclean conditions introduce dirt and other particles into the agent. These impurities disrupt the intermolecular forces of the chemical agent, making the agent more susceptible to environmental factors and rapid decomposition. It is unlikely that a terrorist organization would spend large sums of money for high-end laboratory equipment when it is possible to create crude forms of mustard and sarin in smaller quantities and remain partially undetected.

While the development of chemical weapons agents is relatively easy when compared to biological and nuclear weapons, their effective employment remains difficult. The Islamic State employed chlorine and sulfur mustard 52 times from 2014 to 2016, though their employment was described as "rudimentary."[87] Dissemination of the chemical agents is critical. The Islamic State used "rockets, mortar shells, or artillery shells filled with chemical agents."[88] In these cases, the Islamic State either removed the conventional explosives and filled the rounds with the chemical agent or left some of the explosives in the rounds with the chemical agents. In the first method, the effects of the agents are limited to the immediate area where the rounds impact. The second method exposes agents to the heat and pressure of the detonation of the conventional explosives in the rounds, which causes much of the

81 Forsberg, Driscoll, Webb, and Dean, p. 51.

82 George Musser, "Better Killing Through Chemistry," *Scientific American*, November 5, 2001.

83 "Health Effects of Project Shad Chemical Agent: VX Nerve Agent," National Academies of Science, 2004, p. 13.

84 This figure was found by dividing 2.8×10^8 micrograms (or 280 grams), which is then divided by the LD50 for a 90-kg person of 3.6 micrograms.

85 Forsberg, Driscoll, Webb, and Dean, p. 52.

86 Joshua Gray, Michael Shakarjian, Donald Gerecke, and Robert Casillas, "Chapter 39: Dermal Toxicity of Sulfur Mustard," *Handbook of Toxicology of Chemical Warfare Agents*, Second Edition (Waltham, Massachusetts: Academic Press, 2015), pp. 557-576.

87 Eric Schmitt, "ISIS Used Chemical Arms at Least 52 Times in Syria and Iraq, Report Says," *New York Times*, November 21, 2016.

88 Ibid.

agent contained in the rounds to decompose.

Unmanned aerial systems potentially provide a new method for employment of chemical agents. While drones facilitate the delivery of goods, they are also being used for delivery of fertilizers and pesticides. As the DJI website highlights, "For decades, farmers have either relied on labor-intensive manual spraying or hired crop dusters to spray fields too large for manual labor. Neither option is an ideal one as manual spraying is time intensive while crop dusters are cost heavy. The DJI Agras MG-1 is an agricultural octocopter designed to increase efficiency and manageability in plant protection and fertilization. One single Agras MG-1 can carry 10kg of fluid and cover 10 acres (4 hectares) in a single flight. This is ~60 times faster than manual spraying."[89] While DJI currently has the largest market share of the drone industry, it is not the only manufacturer. Other drones could also be easily modified with tanks, pumps, tubing, and nozzles instead of cameras without significantly altering the flight characteristics of the UAS.

The efficiency of these drones is further aided by advanced tracking and flight programming. Users can now determine a flight path prior to flight using way points, creating a semi-autonomous drone that would fulfill the pre-determined actions of the program. Ostensibly, a terrorist could launch a drone capable of carrying a liquid on a pre-set flight path, releasing its cargo along the way.

Due to the limited range of many drones, the terrorist would likely need to initiate the pre-set flight and leave in order to escape the hazard area. Since December 21, 2015, the FAA has required all hobbyist and recreational drones between 0.55 pounds and 55 pounds to be registered to "enable the FAA to trace aircraft more easily in the event of security or safety incident."[90] This registration ideally prevents such an attack since a no-fly zone could be established over a venue. There is, however, the real possibility that the GPS software tied to the registration could be hacked and altered.

In sum, the applicability to chemical weapons development of the technologies examined by this report lies primarily in UAS use as a delivery mechanism. Chemical weapons material is relatively accessible, at least compared to biological weapons and nuclear material, so the critical hurdle in this category is effective delivery and dispersion. And this is no insignificant hurdle. Aum Shinrikyo, with all of its resources, was successful at producing significant quantities of sarin, but struggled mightily with effective dispersion, ultimately relying on a more rudimentary method for its infamous 1995 attack on the Tokyo subway.[91] At this point in time, much of the discussion about terrorist use of UAS for chemical weapon dispersal is theoretical, as the world has not seen any terrorist group implement this method (although Aum Shinrikyo reportedly explored it[92]), despite the Islamic State having access to both drones and chemical weapons. But given both the increasing advances in UAS capability and the innovative approach to attack methodology and weapons development that this group and non-state actors have shown, this threat seems likely to grow.

Biological

The United Nations defines biological weapons as "complex systems that disseminate disease causing organisms or toxins to harm or kill humans, animals, or plants. They generally consist of two parts – a weaponized agent and a delivery mechanism"[93] Biological warfare is not a modern phenomenon and has been employed by forces for several hundred years. A historical survey of biological warfare

89 "Agriculture Spraying," DJI website.

90 "Registering Your DJI Drone in the U.S.: What You Need To Know," DJI website, December 21, 2015.

91 Richard Danzig, Marc Sageman, Terrance Leighton, Lloyd Hough, Hidemi Yuki, Rui Kotani, and Zachary Hosford, "Aum Shinrikyo: Insights Into How Terrorists Develop Biological and Chemical Weapons," Center for a New American Security, July 2011.

92 Rassler, p. 1.

93 "What are Biological and Toxin Weapons," United Nations Office at Geneva website.

concluded that "the crude use of filth and cadavers, animal carcasses, and contagion had devastating effects and weakened the enemy. Polluting wells and other sources of water of the opposing army was a common strategy that continued to be used through the many European wars, during the American Civil War, and even into the 20th century."[94] One of the most notable uses of biological warfare occurred when the Spanish conquistador Francisco Pizarro gave clothing that was contaminated with smallpox to the Incas in South America. Smallpox was also used during the French-Indian Wars; Captain Ecuyer, on June 24, 1763, distributed blankets laced with smallpox in hopes of diminishing the hostile Indian population.[95]

Biological weapons have continued to be used in recent years, to include the anthrax letters in 2001 and several ricin attacks. Even though the ricin attacks were relatively unsophisticated, the ability of a part-time actress/housewife from Dallas, Texas, and a karate instructor from Tupelo, Mississippi, to extract the toxin from castor beans demonstrates the ease with which some biological weapons can be developed and employed.[96] Ricin is considered a Category B agent/disease, according to the Centers for Disease Control and Prevention, and while relatively easy to disseminate, it only results in "moderate morbidity rates."[97] Conversely, anthrax, Ebola, smallpox, and botulism toxins are considered Category A for their easy dissemination via person-to-person contact and high mortality rates.[98] Ricin was notoriously used in the 1978 assassination of Georgi Markov, a Bulgarian dissident, using an umbrella to inject a pellet under his skin; however, its limited dissemination beyond a single injection point make it an impractical agent for terrorists' use.[99] This has not prevented would-be terrorists from continuing to explore its use, as demonstrated by Tunisian national Sief Allah H. allegedly in June 2018 while residing in Cologne, Germany, and Wahelba Dais, a U.S. legal permanent resident, in Wisconsin in 2019.[100]

Even though many biological warfare agents are endemic to parts of the world, their ability to spread and be transmitted over a wide range is limited. The 2014 Ebola outbreak in West Africa, for example, involved over 28,000 suspected cases and the deaths of over 11,325, but it had limited impact beyond Guinea, Sierra Leone, and Liberia.[101] Ebola is transmitted through direct contact with blood and bodily fluids, yet despite modern transportation, it remained relatively contained. Among many reasons, this was due to the pace at which an infected person becomes symptomatic, an average of eight to 10 days. While an infected person could infect another person when they are pre-symptomatic, the probability of infection is relatively low. As the symptoms of the disease worsen, the amount of virus in the body also increases, but the person tends to become debilitated by the symptoms, reducing the ability to interact with others.

The toxicity, transmissibility, and progression of symptoms of all biological agents differ as their mech-

94 Stefan Riedel, "Biological warfare and bioterrorism: a historical view," Baylor University Medical Center Proceedings, October 2004, pp. 400-406.

95 Ibid.

96 "New Boston, Texas Woman Guilty of Sending Ricin Letters," Department of Justice, December 10, 2013; "Mississippi Man Guilty in Ricin Letter Investigation," Department of Justice, May 19, 2014.

97 "Bioterrorism Agents/Diseases," Centers for Disease Control and Prevention. The United States Centers for Disease Control and Prevention uses three categories to describe bioterrorism agents and diseases. The first category is Category A, which is used to describe the agents and organisms that pose the greatest risk to national security due to their ease of dissemination/transmission from person to person, high mortality rates, and potential for impact on public health. Category B is the second-highest priority. The agents and organisms in this category are "moderately easy to disseminate" and "result in moderate morbidity and low mortality rates." The third category, Category C, includes "emerging pathogens that could be engineered for mass dissemination." See "Bioterrorism Agents/Diseases," Centers for Disease Control and Prevention.

98 Ibid.

99 "The BBC journalist assassinated with a poison-tipped umbrella," BBC, September 21, 2016.

100 Florian Flade, "The June 2018 Cologne Ricin Plot: A New Threshold in Jihadi Bio Terror," *CTC Sentinel* 11:7 (2018); "Wisconsin Resident Waheba Dais Pleads Guilty to Attempting to Provide Material Support to ISIS," Department of Justice, April 22, 2019.

101 "Ebola Virus Disease," Centers for Disease Control and Prevention.

anism of action and structure differ. This difference is derived from the genetic information contained as either DNA or RNA, depending on the pathogen. The field of synthetic biology provides individuals with the tools to manipulate the genetic material of these pathogens.

A 2014 *CTC Sentinel* article, "The Biohacker: A Threat to National Security," identified five potential strategies for the manipulation of biological pathogens: "Wolf in Sheep's Clothing," "Trojan Horse," "Spoof," "Fake Left," and "Roid Rage."[102] As explained in the article:

> *"A 'Wolf in Sheep's Clothing' occurs when a biological organism or toxin is modified through genetic engineering so that it can be expressed in an active form but does not present the normal epitopes."*[103] *"In a 'Trojan Horse,' a biohacker maintains the epitope of a non-threatening agent but re-engineers the active component of the toxin to increase the biological threat without increasing the detectability. The "Spoof" occurs when a benign agent is modified to express epitopes distinctive of a known toxin in order to trigger an unnecessary protective response by the target parties (the local, state, or federal government), while the delivering party (the biohacker) can afford to remain unencumbered. The "Fake Left" is a means to modify through selection or genetic engineering the method of transmission of an organism (for example, one that is typically passed by fluid to an airborne method). Such modification makes it easier to disperse an agent among a target population. The "Roid Rage" strategy aims to potentiate the effects of a common virus by expressing components of a deadly virus, such as expressing Ebola virus RNA sequences into the common flu virus. An infected person would demonstrate symptoms of the flu, hampering early detection and treatment of Ebola and favoring its deadly outcomes."*[104]

Current synthetic biology tools could be used to employ these strategies in order to weaponize a naturally occurring pathogen. While employment of naturally occurring diseases in conflict is not a new concept, what is new is the ability to weaponize, in the sense that synthetic biology can be used to design pathogens to survive in the environment (increasing transmissibility and eluding known treatments) and avoid detection. While these strategies appear simplistic, their actual application is not trivial. Rapid improvements in synthetic biology tools and techniques coupled with the corresponding research released in thousands of publications annually are lowering both the technological and information bar required for manipulating genetic material. This bar will continue to lower over the next five to 10 years, particularly as commercialization leads to more user-friendly techniques and websites that are meant to facilitate research.

To employ one of the previously mentioned strategies to create a biological weapon, a terrorist would first need to know the genetic sequence of the biological pathogen. Knowing the specific sequences of A-T(U)-C-Gs (genetic sequence) of a pathogen is not enough knowledge or skill to modify a pathogen. In order to manipulate the pathogen to have a specific effect, an individual must also know which por-

102 John Wikswo, Stephen Hummel, and Vito Quaranta, "The Biohacker: A Threat to National Security," *CTC Sentinel* 7:1 (2014).

103 As described in Wikswo, Hummel, and Quaranta: "Epitopes are specific amino acid sequences on the surface of a cell, or certain BW agents such as anthrax that invoke a specific immune response. The unique amino acid sequences are identifiable traits of certain BW agents and are viewed as biomarkers. The concept of epitope can be extended to include any amino acid sequence that can be detected though a molecular affinity assay, such as aptamers. See, for example, Larry Gold et al., "Aptamer-Based Multiplexed Proteomic Technology for Biomarker Discovery," *PLOS One* 5:12 (2010). Separately, gene expression dynamic inspection (GEDI) studies (Sui Huang et al., "Cell Fates as High-Dimensional Attractor States of a Complex Gene Regulatory Network," *Physical Review Letters* 94 (2005)) demonstrate that HL-60 under different environmental conditions will present different genes throughout its transformation process to neutrophils, 168 hours later. So identification through gene expression at a given time point would identify two different agents. The concept of gene expression phase space and epigenetic attractors is treated in more detail in Sui Huang and D. E. Ingber, "A Non-Genetic Basis for Cancer Progression and Metastasis: Self-Organizing Attractors in Cell Regulatory Networks," *Breast Disease* 26 (2007)."

104 Wikswo, Hummel, and Quaranta.

tions of the genetic code correspond to which protein following transcription and translation.[105] Since many of these biological pathogens are endemic around the world, their genetic sequences have been studied and subsequently published in a variety of medical and scientific journals in order to identify new treatments. Due to the nature of science publications and competition between researchers, the complete genetic code with corresponding protein output are rarely published in a single journal, let alone article. Consequently, a terrorist would have to be savvy enough to comb through perhaps dozens of journals and databases to understand the full sequence and effects of that sequence.

Identifying the correct synthetic biology tool and designing the correct complementary sequence is the next step in the development of a biological weapon. Not all synthetic biology tools are the same. CRISPR-Cas9 does not work perfectly in all conditions and for all pathogens. Other synthetic biology tools such as zinc-finger nucleases (ZFN) and transcription-activator like effector nucleases (TALEN) may be better suited for altering the pathogen. These ZFN and TALEN tools are bioengineered enzymes, similar to CRISPR-Cas9, that can cleave DNA at a directed sequence using the designed complementary sequence in the DNA binding domain of the protein.

These first two steps are academic and require the ability to navigate scientific literature while identifying the necessary procedures and materials. Application of this knowledge requires another set of skills and equipment such as incubators, polymerase chain reaction (PCR) machines, and tissue culture hoods, to name a few. Much of the equipment used at a university-level research laboratory can be purchased openly. Unlike a gas centrifuge, for example, which has a single purpose—uranium enrichment—there is no distinction between the equipment used for biological weapon agent development and non-nefarious acts. Manipulating DNA to find a cure for cancer uses the same tools as manipulating the DNA of anthrax or Ebola for weaponization. This dual-use nature makes it difficult, if not impossible, to completely prevent nefarious use.

While lab equipment can easily be acquired without drawing attention, acquisition of a Category A pathogen is extremely difficult. Some of the pathogens are naturally occurring, however, these are not pure samples. Most pathogens require a host for survival. For example, a terrorist could draw the blood of someone with Ebola and would technically possess Ebola but not much could be done at that point. The Ebola virus in the small sample would continue to divide using red blood cells as hosts, and the number of viable cells able to host the Ebola virus would be consumed quickly. The virus would need to be isolated/separated from blood cells, serum, antibodies, and everything else in the sample. Only after being isolated could the sample be weaponized, let alone manipulated using synthetic biology to survive widespread dissemination, increase pathogenicity, or suppress symptoms to increase transmissibility.

Another route to the development of biological weapon would be to create the pathogen *de novo*, similar to Dr. Evans and his horsepox experiment. For this to occur, a terrorist would still be required to know the pathogen's genetic sequence and how to manipulate the synthetic biology tools in order to anneal the genetic sequences together in a cellular host.

Simply having the tools, knowledge, and perhaps the naturally occurring pathogen on-hand does not instantly mean success. Contamination, whether introduced by the scientist, a manufacturer, or a result of the environment, often ruins the best designed experiment. Even the most highly trained scientists are human and are often the prime source of contamination. One can then imagine the contamination risk involving someone who is inexperienced, poorly trained, and/or in an austere setting. An inconsistent power system, for example, could cause even a short-term power loss in an incubator during which samples might easily die.

105 Transcription and translation are steps required for gene expression. Transcription is the process of copying a specific DNA segment to RNA, whereas translation is the process that ribosomes use to produce an amino acid sequence from the RNA. The amino acid sequence will then fold upon itself into a specific protein based on the covalent bonds and intermolecular forces, such as dipole-dipole interactions, that hold the structure together.

While a community lab may provide a terrorist with the necessary equipment in a non-austere environment, it does open him up to prying eyes and oversight. To develop a biological weapon in a community lab would require the terrorist to piecemeal the project in such a way to conceal true intent. By fragmenting the construction of a biological weapon, the terrorist increases the risk of failure since biological material easily degrades if stored improperly or outside of a host for extended periods of time. To use this method, a terrorist would require years of lab work beyond the graduate level in order to not only plan the development of the weapon but to also troubleshoot the process when errors occur.

Assuming a terrorist or its supporting organization is able to modify or *de novo* construct a biological agent, the next major step would be delivery of the pathogen. Unless in spore form or a pure toxin, a biological weapon agent requires a host to survive. Person-to-person transmission, while 'effective' with recent Ebola and SARS outbreaks, is limited. The host in this case will start to exhibit symptoms of the disease, and the sicker the individual is, the greater the amount of pathogen in the system. Sick people, however, struggle to travel inconspicuously, and the public's natural inclination is to avoid overtly sick people.

Another means of delivery is to use drones, similar to those used for delivering pesticides. This method poses physical challenges. While it is possible to suspend a pathogen in a fluid to be extruded through a nozzle, this process requires pressure to push the pathogen through the nozzle. Pushing the fluid under pressure would provide the greatest dispersion of the pathogen but would also cause physical strain on the pathogen. The torsion and pressure exerted on the plasma membrane and proteins of the pathogen in solution could easily overcome the intermolecular forces and covalent bonding holding the molecules together.[106] Perforation of the membrane or disruption of the proteins would not only make the pathogen ineffective, but also leave it targeted for degradation.

To be effective, a terrorist would need to test delivery of the weapons agent to determine if the pressure of the system is inactivating the pathogen. Such testing is dangerous from an operational security perspective, potentially causing an unanticipated release of the pathogen and effecting the terrorist or unwittingly drawing scrutiny. Additive manufacturing could enable the terrorist to design and print dispersion nozzles that exert less torsion on the pathogen, but this would remain theoretical until and unless the nozzle were tested.

The current state of synthetic biology is that a knowledgeable user who is trained in lab work and who has access to the necessary lab equipment could, with minor difficulty, develop and employ a biological weapon. Dr. Evans' *de novo* synthesis of horsepox demonstrated this fact. Terrorist organizations such as the Islamic State may have some knowledge, some training, and some access to lab equipment but are not likely to have all three at sufficient levels. While individually these components of a bio-terrorist are difficult to identify, collectively they begin to present a signature.

The future state of these technologies, particularly synthetic biology, presents a different picture. Synthetic biology tools are becoming easier to understand and manipulate by the day. Lab equipment no longer needs to be purchased through vendors; rather, it can be printed clandestinely using additive manufacturing. Unmanned aerial systems are becoming so common that their novelty is fading, and it is possible that drones flying overhead will become such a common occurrence that few will question their presence. Under the current state of progression and monitoring, the risk of a terrorist developing and employing a biological weapon, while small currently, is consequently increasing with every year.

106 S. Stewart, Sergey A. Grinshpun, Klaus Willeke, Snejana Terzieva, Vidmantas Ulevicius, and Jean Donnelly, "Effect of impact stress on microbial recovery on an agar surface," *Applied and Environmental Microbiology* 61:4 (1995): pp. 1,232-1,239; R. C. Stone and David L. Johnson, "A note on the effect of nebulization time and pressure on the culturability of Bacillus subtilis and Pseudomonas fluorescens," *Aerosol Science and Technology* 36 (2010): pp. 536-539.

Concluding Analysis and Potential Solutions

"Nobody understands the limits of these technologies, so how do you address the threats?"[107]

— Former Deputy Assistant Secretary of State Mallory Stewart, 2018

Over the next five to 10 years, these technologies (and many others) will change society dramatically worldwide. Delivery and manufacturing costs of goods will become faster and cheaper. Delivery times will be measured in hours instead of days. Additive manufacturing will enable remote areas around the world to have access to goods such as repair parts without having to wait on a difficult supply chain. Synthetic biology will enable researchers and pharmaceutical companies to target thousands of genetic-related diseases. New drugs will be developed faster and less expensively while unmanned aerial systems will likely facilitate their delivery. The commercialization of synthetic biology, additive manufacturing, and unmanned aerial systems drives the availability and usability of these technologies. The requirement for highly skilled scientists and manufacturers to use these technologies is rapidly disappearing, while the hobbyist communities for these technologies grows. While the potential good of these technologies seems limitless, so too are the potential pitfalls. And as has been examined in this report, some of those pitfalls include their applicability to WMD proliferation, especially regarding chemical and biological weapons. As John P. Caves and W. Seth Carus highlight in *The Future of Weapons of Mass Destruction: Their Nature and Role in 2030*, "Chemical and biological weapons, which heavily utilize dual-use technologies, are most likely to feature in any future WMD terrorism incident."[108]

Figure 2: Shifting risk of WMD terrorism in next five to 10 years

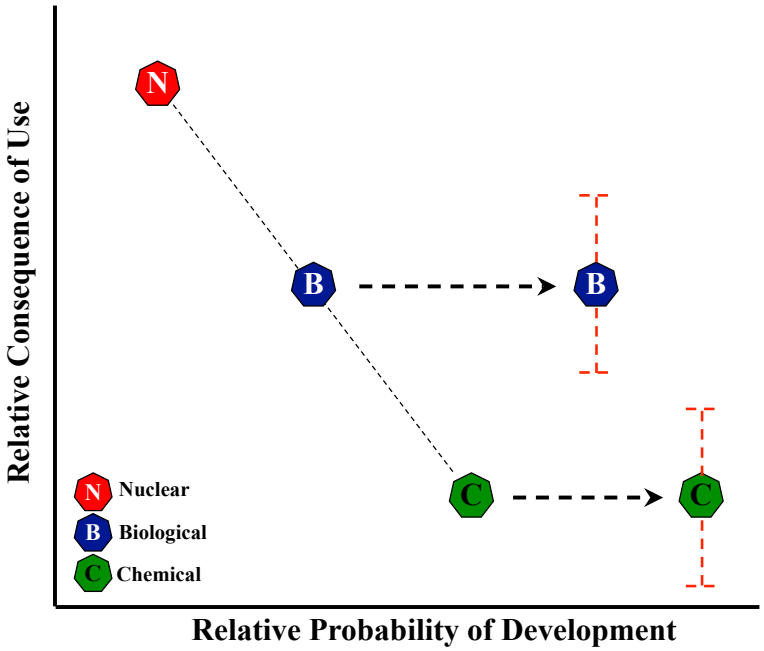


Figure 2 illustrates the shifting risk (dashed arrows) and uncertainty for WMD development and employment in the next five to 10 years. These emerging technologies will lower the material and

107 Author interview, March 2018.

108 John P. Caves, Jr., and W. Seth Carus, "The Future of Weapons of Mass Destruction: Their Nature and Role in 2030," Occasional Paper 10, National Defense University, March 2016, p. 45.

intellectual threshold for development of both biological and chemical weapons agents, yet the consequence of their use remains unclear, as indicated by the dotted red error bars. These same technologies will also be used simultaneously to develop medical counter-measures and detection capabilities. The risk of developing a nuclear weapon remains unchanged over this same period since access to special nuclear material remains the largest limiting factor.

Much of the risk and threat associated with these dual-use technologies resides in the intent of the user. Consequently, there is no silver-bullet solution to prevent terrorists from using these technologies in some form or another to develop and/or employ a weapon of mass destruction. Only through a whole-of-government approach at the local, state, and federal level is prevention possible. The approach would require multiple lines of effort that are mutually supporting and focus on both prevention and response to an attack.

The first line of effort is outreach and cooperation between consumers, the do-it-yourself communities, scientists, corporations, and governments. This line of effort needs to not only highlight the ethical norms and potential dangers associated with terrorist acts but also provide incentives for ethical use and reporting. For example, the do-it-yourself community or academic institutions could possibly receive tax incentives or rebates for registering/reporting the types of experiments being conducted or receive similar incentives for conducting ethical use training on an annual basis. Within the drone community, users could receive rebates for the number of safe flight hours away from no-fly zones. Similarly, the additive manufacturing industry could receive incentives for reporting use of materials or designs that could be used to make centrifuges or other uranium isotope separation process equipment. The United States is far from the only user and developer of these technologies, so outreach would ideally be international. The goal of outreach is first and foremost prevention but also to keep individuals from using these technologies in secret.

Additionally, it is necessary for individuals at the local, state, and federal level to not only know what these technologies are and their pitfalls, but also the necessary support equipment for these technologies. A firefighter responding to a suspicious smell, for example, may not directly recognize that synthetic biology is being used to modify a virus, but should be able to identify isolation hoods, centrifuges, and PCR equipment. Similarly, FBI agents in the field need to also understand the effects of accumulating equipment and knowledge while working with industries to understand what is available on the open markets. The commercialization of these technologies internationally means that military units are also likely to encounter AM and synthetic biology tools on targets overseas.

The second line of effort attempts to address the dual-use nature of these technologies. While these technologies are intrinsically dual-use, under certain configurations their only function is to produce some component required for WMD production. For example, the only purpose of possessing smallpox's genetic sequence today is to produce smallpox. While it is possible for a highly skilled scientist to *de novo* synthesize the entire sequence, it is not likely a terrorist would pursue this route. Instead, a terrorist would likely purchase smaller and more manageable portions of the gene sequence from different companies and force annealing of these segments using synthetic biology tools. While the International Gene Synthesis Consortium (IGSC) members "screen the complete DNA and translated amino acid sequences of every double-stranded gene order against the IGSC's comprehensive curated Regulated Pathogen Database derived from international pathogen and toxin sequence databases," this is not a requirement.[109] According to its website, the IGSC consists of approximately only 80 percent of "commercial gene synthesis capacity worldwide."[110] With the growth of the synthetic biology industry overall, the other 20 percent is an ever-increasing number of businesses.

109 "About," International Gene Synthesis Consortium. The IGSC is "an industry-led group of gene synthesis companies and organizations formed to design and apply a common protocol to screen both the sequences of synthetic gene orders and the customers who place them." See "About," International Gene Synthesis Consortium.

110 Ibid.

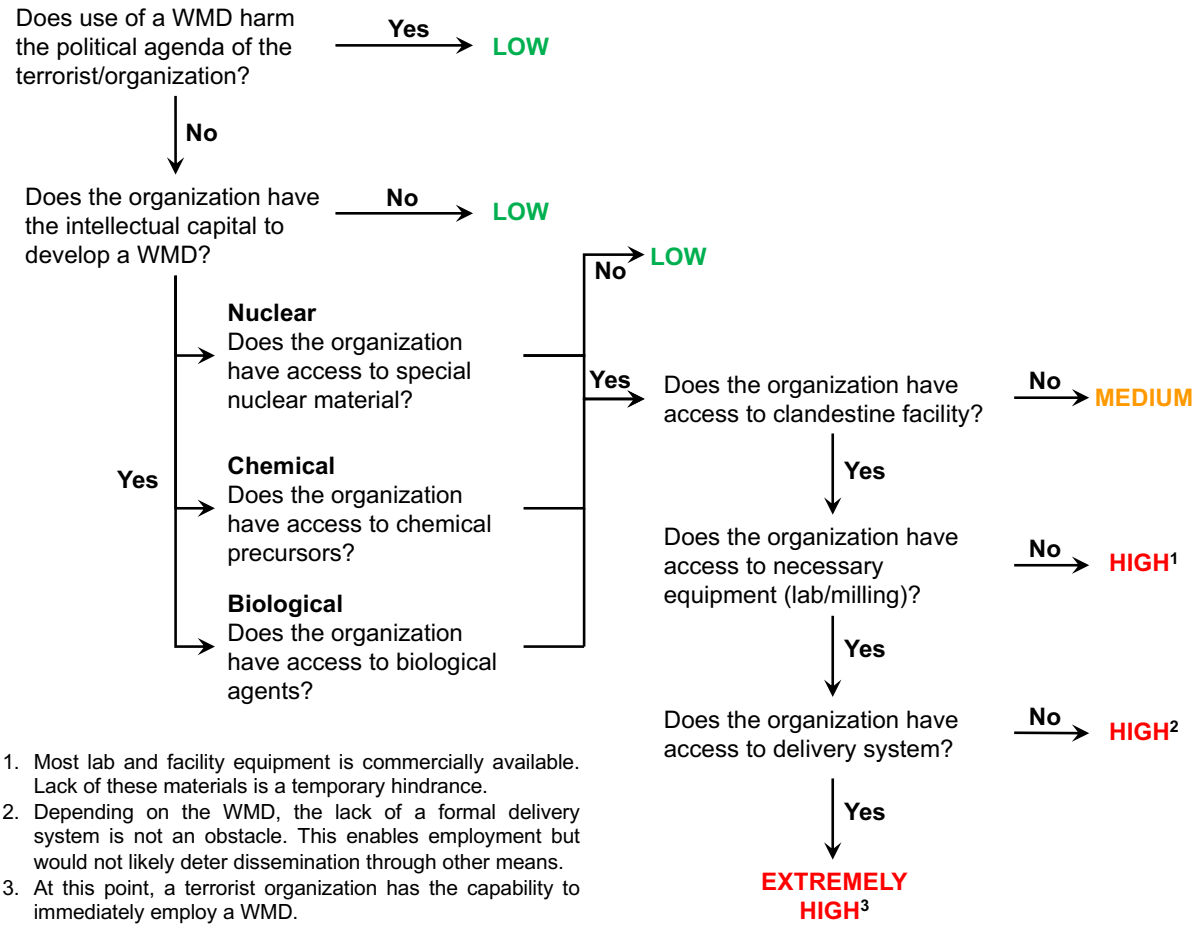
While most commercially available drones are used for benign purposes, such as photography, other versions that are used for delivery of pesticides could be modified for delivery of a chemical or biological weapon agent. Since this use requires little to no modification, this configuration of an unmanned aerial system needs further restrictions such as export control. Only once the critical configuration or model of the technology has been identified is it possible to establish both the physical and policy safeguards required to prevent nefarious use. This is not a simple line of effort, but a necessary one.

The third line of effort to prevent or deter a WMD attack is possessing the ability to respond. These technologies need to be leveraged to respond to a WMD incident. A drone, for example, could be used to map the plume in a nuclear attack, enabling first responders to identify areas of low radiation or to deliver medicine to individuals exposed to either a chemical or biological agent. Synthetic biology could also be used rapidly and at low cost to develop medical counter-measures. The ability to respond rapidly and efficiently to minimize the effects of the WMD is a deterrent against its usage. A terrorist is not likely to spend the time, effort, and cost required to develop a WMD if the effects could be quickly mitigated. A comprehensive response able to deploy rapidly limits the psychological effects of a WMD, diminishing one of the critical goals of a terrorist act.

The final line of effort lies in attribution. Weapons of mass destruction have signatures that correspond to their origin. Post-use forensics is crucial for attribution. The signatures created by chemical and nuclear processes that create these WMD are generally traceable. Biological weapons, unlike nuclear and chemical weapons, tend to be harder to ascribe to their creator because many pathogens are naturally occurring. Use of synthetic biology tools to modify the agent, however, create a signature. No two scientists are likely to design genetic primers, which guide the gene editing tool such as CRISPR to the editing site, the same way; consequently, a potentially unique signature exists. The databases for nuclear debris and chemical residue are currently robust, and collection of material for attribution is exercised regularly. Existing databases need to be expanded with agents modified by these emerging synthetic biology tools in order to have a comparison.

Determining the risk associated with a terrorist employing a WMD is dependent on several factors: technical expertise, availability of materials, delivery capability, and political will, just to name a few. Apart from a conventional terrorist attack, nuclear, biological, and chemical weapons each have their own associated risk. And as emerging technologies such as synthetic biology, additive manufacturing, and unmanned aerial systems progress over the next five to 10 years, it is important to constantly reassess their impact on the ability to develop a WMD. While nuclear weapons, for example, will continue to be constrained by the necessity for significant quantities of special nuclear material, the barriers preventing chemical and biological weapon development and employment are being lowered.

Figure 3: A proposed process for assessing the risk of a terrorist or terrorist organization developing and employing a weapon of mass destruction



1. Most lab and facility equipment is commercially available. Lack of these materials is a temporary hindrance.
2. Depending on the WMD, the lack of a formal delivery system is not an obstacle. This enables employment but would not likely deter dissemination through other means.
3. At this point, a terrorist organization has the capability to immediately employ a WMD.

Figure 3 provides a simplified flow chart for risk associated with terrorists developing a WMD. This chart is over-simplified for the purposes of demonstration, but depicts the multiple levels of developing a WMD, to include the intellectual capacity, raw material, access to specific equipment, and delivery system. A terrorist or terrorist organization must overcome multiple hurdles in order to develop and employ a WMD. This assessment must also be put in context of potential targets which may affect the likelihood of an attack

Commercialization of synthetic biology, additive manufacturing, and unmanned aerial systems will continue to reduce both the intellectual and material barriers that currently hinder WMD proliferation. And while these technologies may enable WMD proliferation, their ability to improve society are unparalleled. This intrinsic dual-use nature makes ignoring or banning these technologies an unlikely option. Instead, these tools need to be embraced. It is important to understand that emerging technologies are also not stochastic, rather they are interdependent not only in their development but also their use. While this report focused on synthetic biology, additive manufacturing, and unmanned aerial systems, these are not the only technologies that reduce the barrier for WMD proliferation. Micro-scale chemistry and information-sharing applications, to name two, will further reduce the barriers to WMD development and employment. Consequently, as new technologies emerge, it is important to ask the questions: what about this technology can be used to proliferate WMD, and are there means to limit the nefarious use of this technology by terrorists?

Combating Terrorism Center

AT WEST POINT