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Army Officer Corps Science, Technology, Engineering and Mathematics (STEM) Foundation Gaps Place Countering Weapons of Mass Destruction (CWMD) Operations at Risk – Part 2

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About the cover: An image of the May 25, 1953, test-firing of the M65 atomic cannon called "Atomic Annie".
Picture from: National Nuclear Security Administration

Inside the Journal

Director Notes

COL Benjamin Miller
Director, USANCA

The United States Army Nuclear and Countering Weapons of Mass Destruction Agency's (USANCA's) efforts in countering nuclear and weapons of mass destruction remain front-and-center as world events continue to unfold in Europe, the Middle East and the Pacific. The conflict continuum and the range of military operations are moving rapidly in multiple directions. The implications on military alliances, engagements, security cooperation efforts and deterrence drive discussions of policy, defense and security. Countering weapons of mass destruction (CWMD) and conventional nuclear integration doctrine, training and education are critical to inform Army leaders on both friendly and adversary capabilities and capacities. This knowledge enables the United States Army and the Joint force to gain competitive advantage across the spectrum of operations, now and into the future. USACNA's dynamic and impactful efforts in conventional nuclear integration, survivability, Army reactor oversight, leader development, international engagement and proponency, coordinated throughout the enterprise ensure synchronization and proactive actions address CWMD threats and challenges throughout the Joint, Interagency and International community of interest.

Russia's unjustified invasion of Ukraine also serves as a stark reminder for the importance of strategic nuclear deterrence and the challenges of preparing for uncertainty against a nuclear-armed adversary intent on achieving its objectives. USANCA continues assisting and leading the Army in a wide range of initiatives aimed at maintaining nuclear deterrence and mitigating risks, denying benefits, and imposing costs on any adversary that miscalculates the Army's ability and will to fight and win in the face of nuclear weapon employment. See article "The Army's Place on the Nuclear Battlefield" as an example of the doctrine and education work we are doing across the Army.

Survivability is on the forefront for Army Senior Leaders. We are taking a hard look at the responsibilities within the chemical, biological, radiological and nuclear (CBRN) Survivability Program to ensure that expertise is being applied in an appropriate manner to meet the needs of the ground commander. As a result of the introspection, we realize that while a lot of great work was accomplished in coordination with the acquisition community to include appropriate requirement language in the development documents for follow-on test and evaluation and reporting schema, we have not applied enough time and attention to helping the ground commanders understand the survivability of their current force. Operational survivability is our translational science bridge between the acquisition strategies and the "on-hand" capabilities (both personnel and materiel) expected to fight, survive, and win in and through CBRN contaminated environments. Applying the lens of operational survivability helps nuclear weapon effects modelers analyze the various threat phenomenologies and develop richer preclusion analysis products for senior leaders.

USANCA is proud to be heavily involved in the Army Reactor Program, which is decommissioning two deactivated nuclear power plants. We are thrilled to be partnered with the professionals within the United States Corps of Engineers Baltimore District in these two projects. These power plants are a part of the proud Army Nuclear Power Program history. Although the Army Nuclear Power Program was discontinued in 1976, the lessons learned provide Army stakeholders valuable insights as the Department of Defense pursues advanced reactor technologies.

Sharing information among the CWMD community is one of the best aspects of USANCA. The CWMD Advisor Course has been re-energized as we emerge from the pandemic years. We have an aggressive schedule planned to teach the course through resident courses at USANCA and on the road via mobile training teams. The course, awarding Army service members with the coveted D1 Army Skill Identifier, continues to be well-received and we look forward to "taking the show on the road."

The North Atlantic Treaty Organization Joint Chemical, Biological, Radiological and Nuclear Defense Capability Development Group (NATO JCBRND-CDG) and its seven subordinate panels kicked off its Spring 2022 cycle of meetings at NATO Headquarters in Brussels 21-23 February 2022 led by USANCA serving as U.S. Head of Delegation. The seven panels remain focused on developing NATO CBRN-related standards to enhance interoperability for the Alliance and its partners. In addition, the writing team for the new NATO Allied Joint Publication, (AJP) 3.23 ALLIED JOINT DOCTRINE ON COUNTERING WEAPONS OF MASS DESTRUCTION IN MILITARY OPERATIONS, also met and set a goal to complete a final draft prior to ratification by the end of the calendar year 2022.

Over the course of my time serving as the USANCA Director, I have seen a marked increase in the demand for FA52 officers. This is a testament to the professionalism and the quality of the work that our officers provide. Recent events have acutely shown that our adversaries still view WMD capabilities as critical for them to achieve their own national objectives. Senior leaders across the Interagency, Joint Force, and the Army are supportive of change in order to address our own capability gaps and vulnerabilities as well as training and manning shortfalls in order to prepare for the future battlefield. FA52s are leading that change. Related to that, we are taking a hard look at our authorizations to ensure that we have our people in the right places. We may see some modest growth over the next couple of years. We must not squander the opportunity we have right now and I am confident that you are all prepared to meet these challenges. I encourage you to write and contribute to our professional journal as a means to exchange ideas and unique knowledge. I look forward to reading your articles and hope this issue advances the dialogue and insights to counter weapons of mass destruction. This will be my last Issue of the Journal on my watch. It has been both an honor and a privilege to serve as the USANCA Director over the last two years. As I transition into retirement, I am confident that the organization will continue to increase the Army's ability to fight and win in contaminated environments Thank you all for your dedication, professionalism, and expertise.

The Army's Place on the Nuclear Battlefield

MAJ Terrence Nolan
LTC Jason Wood

U.S. Army Nuclear and CWMD Agency

Abstract

This paper seeks to demystify the threat posed by nuclear weapons effects, describe the steps the Army must take to modernize for a fight that may include nuclear weapons employment, and offer information and resources to enable commanders and staffs to prepare our formations to fight and win on such a battlefield.

May, 3, 2018, Servicemen of missile formation, Western Military District, executed a successful launch of the Iskander-M ballistic missile at the tactical complex on Kapustin Yar in the Astrakhan region. Russia delayed its 2021 strategic nuclear forces exercise to coincide with its invasion of Ukraine in February 2022. Source: Russian Federation Ministry of Defense.

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Introduction

The United States Army became a non-nuclear force in its divestiture of all nuclear artillery and nuclear short range ballistic missiles following the 1991 Presidential Nuclear Initiatives. When combined with the thawing relationships with Eastern Bloc nations, the idea of fighting on a nuclear battlefield quickly faded into the post-Cold War transition of the 1990s [1]. The attacks on September 11th, 2001 would accelerate this transition as the nation's attention was consumed by the War on Terror for the next two decades.

Today, as the Nation continues its focus on Great Power Competition following the War on Terror, the Army must confront a very different security environment. Herein it supports the strategic deterrence of a revisionist Russia, ascending China, and rogue Democratic People's Republic of Korea who, in addition to Iran, "…are enhancing and exercising their military, cyber, and other capabilities, raising the risks to US and allied forces, weakening our conventional deterrence, and worsening the longstanding threat from weapons of mass destruction" [2].

Collectively, these nations possess a diverse range and growing number of weapons of mass destruction. Of the traditionally accepted weapons of mass destruction (chemical, biological, radiological, nuclear) [Endnote 1], nuclear weapons pose a uniquely significant risk due to their inherent destructive power which is amplified by years of minimal prioritization by an Army fighting decades long counterinsurgencies. US and allied forces train with special equipment (personal protective equipment, detectors, vaccines, etc.) to operate in chemically and biologically contaminated environments and have long incorporated chemical and biological weapons in training and exercises throughout the last 30 years [1]. That is not the case when it comes to nuclear. This neglect has led commanders to believe that the environments created by nuclear phenomenology (blast, thermal, radiation), leaves no option but "…to endure the blast, heat, and radiation, and hope that you are far enough away to survive" [1].

While unthinkable just 10 years ago, the Army must prepare for the use of a nuclear weapon in a regional conflict – the most likely scenario laid out in the 2018 Nuclear Posture Review [3]. In conflict, nuclear weapons use would almost certainly create effects in the land domain where Army forces operate during large scale combat operations. Further, effects in the human dimension require education, training and leadership to sustain our forces' will to fight. To ignore these implications would be professional malpractice. Worse, failure to prepare for this most dangerous enemy course of action would serve to incentivize an enemy by creating a perceived advantage of nuclear weapons use over an unprepared land force. Long a pillar of strategic deterrence through demonstrating conventional capability, the Army must adapt to demonstrate its ability to apply that considerable might in a nuclear environment.

The Security Environment

Alluding to an upcoming Cold War wherein the US, Russia and perhaps even China harbor large arsenals of strategic nuclear weapons is an oversimplification of what has changed in the last 30 years. Should the nuclear-weapon states [Endnote 2] of the world conduct a full and complete strategic nuclear exchange, life would indeed be indelibly altered. However, for the Army, and within the confines of a regional conflict, there is now a very real possibility that a small number of lower yield weapons could be employed on the battlefield with very few effects extending beyond the immediate area. Our adversaries know this and their investment in their nuclear weapons programs show that at a minimum, they value possessing such capabilities. While the US has not diversified its

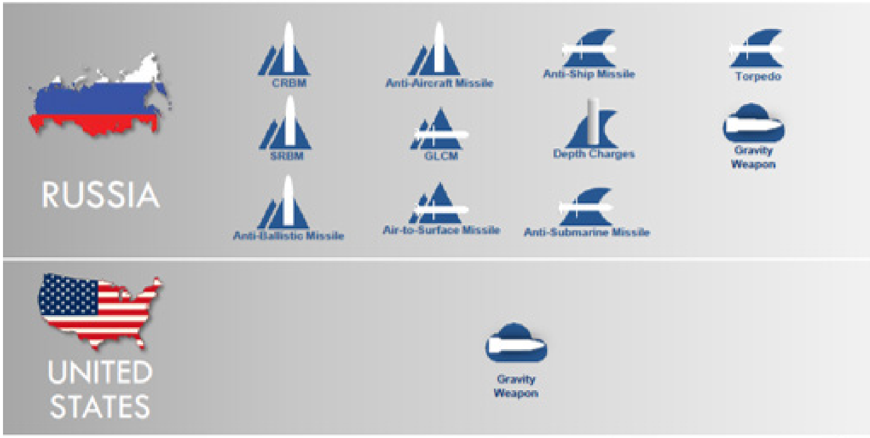


Figure 2. Russia's non-strategic nuclear Challenge, Source: NPR, 2018

nuclear weapons arsenal since 2010, Russia, China and North Korea have continued to develop strategic and non-strategic systems across the ground, sea and air (see figure 2).

Russia in particular has diversified and expanded its non-strategic nuclear weapons [Endnote 3] arsenal as a counter to what it perceives as its conventional inferiority to NATO [2] (see figure 3). In 2019, the Defense Intelligence Agency estimated that Russia had up to 2,000 non-strategic nuclear warheads on a variety of delivery systems "…modernized with an eye towards greater accuracy, longer ranges, and lower yields to suit their potential warfighting role" [4]. The 2018 NPR assessed that Russia believes this diverse and large number of systems provides a coercive advantage in conflicts below total war [3]. Further, these non-strategic nuclear weapons are carried on dual-capable [Endnote 4] systems which make accounting for their nuclear payloads by treaty inspection, or during a conflict, exceptionally difficult [4].

More recently, multiple organizations have assessed that China has begun concerted efforts to expand its triad. Its construction of more than a hundred silos across the country [5] and investments across its nuclear triad indicate that China seeks parity with Russia and the US in every facet of military power, to include nuclear weapons. It remains to be seen if they perceive the same gap that Russia does with respect to a capability advantage, or if they believe the development of non-strategic delivery systems benefits them in some other way. Despite their "no first use" declaratory policy, their interpretation of that policy is still not well understood [6]. Given that some of their non-strategic systems (e.g. the DF-26 Intermediate Range Ballistic Missile) are also dual-capable, the question remains if China would perceive a conventional strike on a dual-capable system carrying a nuclear payload as nuclear counterforce [Footnote 5], and justify retaliation with nuclear weapons [7]. The question is no different for Russia.

Today, the U.S. finds itself in a security environment, deterring multiple adversaries armed with nuclear weapons that are actively diversifying and growing their nuclear arsenals to parity with the US and NATO, and/or to exploit a perceived gap in U.S. and allied capability. The Army supports this strategic deterrence with leaders that largely lack education in nuclear weapons effects and have poor understanding of the impacts those effects would have on the warfighting functions. As the nuclear forces of the US continue nuclear operations to deter our adversaries, its non-nuclear (conventional) forces deter by demonstration of their considerable capabilities. The Army, as the largest US conventional force, can support nuclear deterrence by demonstrating those capabilities while training to operate in a nuclear environment.

Thus, it is imperative that the Army demonstrate its ability to both operate in a nuclear environment and support joint nuclear operations to employ nuclear weapons, if directed by the President under extreme circumstances [3]. In order to do so, it must leverage its existing competencies to implement nuclear-related topics that address the ability of forces to operate under the threat, or employ-

> *"This is America. We have the greatest industry, the greatest innovators in the world and we're going to do what's necessary to create the capabilities that help us maintain the competitive edge going forward."*
>
> *Secretary of Defense Lloyd Austin, Dec 2021*

ment, of nuclear weapons. For the warfighter, these topics cannot be limited to lofty discussions of deterrence. They must apply science-based understanding of nuclear effects gained over decades of U.S. nuclear testing. They must enable a Platoon Leader to look his or her formation in the eye and say "Follow Me" with confidence. The Army must look to the future to understand, across the levels of war, how to modernize leader development, conduct training and develop exercises to enable multi-domain operations in support of the joint force [Footnote 6]. This is the Army's proven method to ensure soldiers are best prepared to operate in a combat environment, and the nuclear environment should be treated no differently.

Nuclear Weapon Phenomenology and Effects

One of the first obstacles to overcome in this discussion is the collective gap in professional training and education where matters of nuclear weapons are concerned. Through no fault of their own, Army leaders' understanding of nuclear effects is based almost completely on depictions of nuclear weapons in popular culture. For better or worse, Hollywood has educated our Army more than we have.

Most believe that nuclear weapon detonations will result in unimaginable devastation that irrevocably alters the landscape, and that clouds of radioactive fallout would make large portions of the earth uninhabitable for centuries. This is patently false. In spite of the destruction or Hiroshima and Nagasaki, and in testament to the strength of their people, these Japanese cities are beautiful, thriving metropolises today. At the Nevada Nuclear Security Site (formerly the Nevada Test Site) more than 1,000 nuclear weapons were tested in 40 years, the last in 1992 [8]. It is toured today without the need for radiation monitoring whatsoever. Hollywood often conflates the effects of weapons fallout with that of nuclear power plant meltdown. For comparison, at the time of the Chernobyl accident it contained 192 tonnes of nuclear fuel in its core [10] which continues to slowly fission, whereas a nuclear weapon may contain upwards of 50 pounds [11] and completely fissions in a fraction of a second. The difference in these radiation hazards' size, and duration is significant.

Nuclear weapons differ from conventional explosives in several ways beyond the size of the explosion. In addition to blast and shock effects at scales much greater than a conventional explosive, nuclear weapon detonations produce intense radiation, electromagnetic pulse (EMP) [Footnote 7], and then residual radiation created by debris and activated material. The extent of these effects

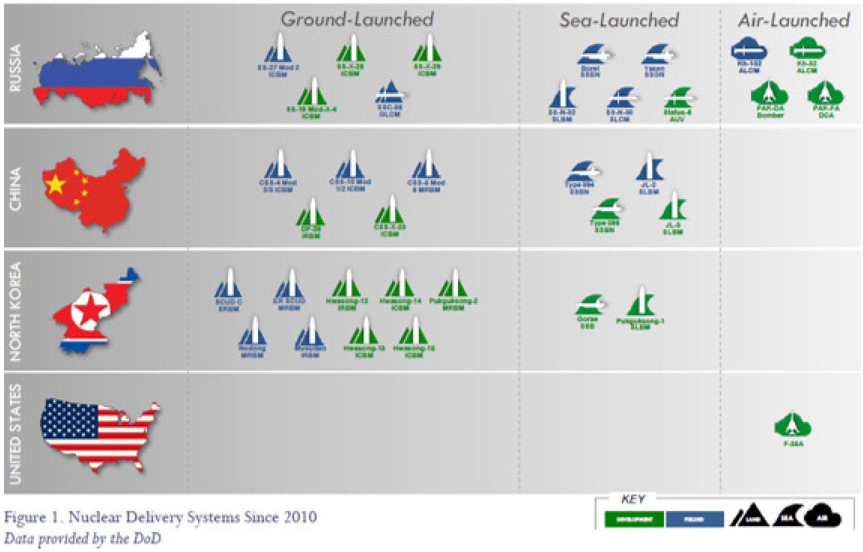


Figure 3. Nuclear Delivery Systems since 2010, Source: NPR 2018

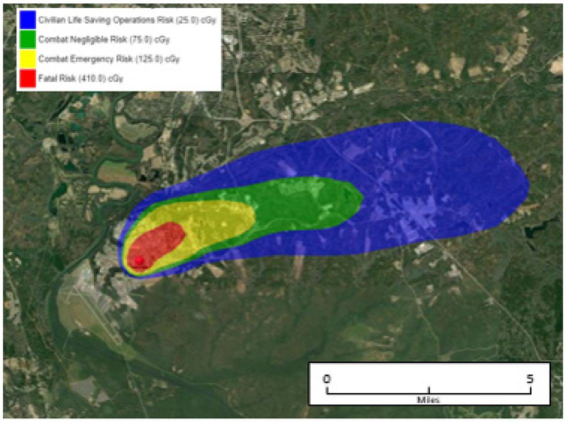
will vary depending on many factors to include the yield of the weapon, its height of burst, and the environmental and physical conditions of the detonation area. Commanders and staffs can find a more in-depth description of these effects in newly released multi-service doctrine, which provides a guide for tactical military forces to plan for operations in a nuclear environment [Footnote 8]. For the purposes of this paper, a brief description of each effect is given to provide sufficient context to discuss mitigation measures in the following sections.

The first effect resulting from a nuclear device detonated on or near the surface of the earth is an intense flash of thermal radiation (heat and light) that constitutes about 35% of its total energy. As light and radiative heat travel at the speed of light, this effect is essentially instantaneous, and can cause burns to personnel and ignite flammable objects. The intense burst of light associated with the detonation can also cause eye injuries resulting from temporary disorientation to permanent blindness.

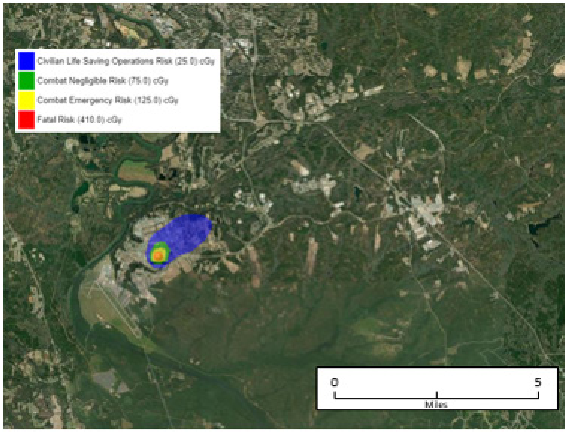
Simultaneously, intense, invisible radiation is released by the detonation. This initial radiation can be harmful to personnel if absorbed in sufficient quantity, and can interact with the environment to create additional radioactive material directly below the detonation. This effect is short lived and no longer of concern after the first minute. Following the initial blast of heat and light, there is a pause, the length of which depends on the distance from the observer to the detonation, before the arrival of the blast wave which is formed from 50% of the detonation's energy. This blast wave radiates outward from the point of detonation and causes injury and damage from extreme pressures generated by the wave front (referred to as over pressure) that can crush objects, and strong winds (referred to as dynamic pressure) that can topple and launch objects through the air (referred to as missiles).

Nuclear detonations near the earth's surface also produce localized EMP through ionization of the atmosphere. EMP can damage unprotected electrical equipment and disrupt communications though the effect will often be secondary to the other effects previously discussed due to its limited range when the detonation is at a low altitude. EMP is a larger concern for nuclear detonations at high altitudes which can produce effects over very large areas that could damage electrical systems of unprotected systems.

The remainder of energy from a nuclear detonation is residual radiation, commonly referred to as fallout. During the fission process that creates the nuclear detonation, special nuclear material [Footnote 9] is split in to thousands of smaller, highly radioactive fragments. If the fireball of the weapon does not touch the ground, these fragments that are vaporized by the intense heat of the fireball, will form minute particles that ride high into the upper atmosphere, spread over a large part of the planet and rapidly decay to negligible radioactive levels. This height above the ground is referred to as a "fallout safe height of burst" and implies no deposition of material in quantities sufficient to affect military operations. Should the fireball contact the ground, these va-



(a)



(b)

Figure 4. Expected absorbed dose for an 8-hour stay starting two hours (a) after a detonation and 48 hours (b) after a detonation. Red regions indicate unprotected personnel would absorb a potentially lethal dose of radiation in an 8-hour period."

porized particles mix with additional vaporized material from the earth's surface, rise into the atmosphere, condense into relatively large particles and fall back to earth in varying concentrations as they are transported by the weather across the general region of the strike. Fallout can create areas of significant radiological hazard due to its extremely radioactive nature and must be accounted for in military operations.

This is where Hollywood most often gets the science wrong. The products of fission are so radioactive that they have a very short half-life – this is, by definition, what makes them so radioactive. Their short half-life indicates that they decay quickly into less radioactive material. A common rule of thumb developed from US nuclear test data is used to estimate radioactivity from fallout demonstrates this phenomenon. It states that for every seven-fold increase in hours following the detonation, there is a 10-fold decrease in the dose rate, a measure of radioactivity, of that radiation. By that rule, fallout is 100 times less radioactive after 49 hours – about two days, and 1,000 times less radioactive after about two weeks. Thus the vast majority of militarily-significant fallout will decay away within the first few days, greatly reducing the hazards to forces. Figure 4 demonstrates this rapid decay of the radiation hazard using a simulated 10 kiloton ground burst. As the diagrams show, the hazard from the strike is almost completely gone after a few days.

Mitigation Measures

As we often say during the Theater Nuclear Operations Course [Footnote 10] instruction, the use of a nuclear weapon by an adversary does not relieve a unit of the responsibility to accomplish its mission. While intra-theater nuclear use will certainly have strategic implications, Army formations must still accomplish the missions they were performing before the detonation. Commanders and staffs must consider the concept of operations those forces use to achieve objectives, as weapon effects can affect key terrain, combat power and lines of communication.

The first step in training for this environment is to understand that this is not a problem CBRN enablers can solve on their own. The lone CBRN Officer in an infantry battalion cannot solve this problem. While that officer is likely the best trained source of information on the weapon's effects, this problem touches all warfighting functions. Officers, NCOs, and Warrant Officers at all levels of command must have some understanding of nuclear effects to apply their subject matter expertise to the problems facing the unit. While that CBRN Officer may be able to describe the effects of the nuclear weapon, staff experts must be able to form schemes of maneuver, sustainment, air defense, etc. given those effects. This is no different than addressing the direct or indirect fire threat.

> *Although our Army still maintains overmatch, it is fleeting. In the face of determined adversaries and accelerating technological advances, we must transform today to meet tomorrow's challenges. Future conflicts will manifest at longer range, across all domains, and at much greater speed, both physical and cognitive. We must therefore continue to implement a 21st century talent management system, develop and field new weapon systems, transform our doctrine, build new organizations, and change the way we train.* [12]
>
> *GEN James C. McConville, Chief of Staff of the Army*

Fortunately, the Army has recognized this gap and recently published its first nuclear doctrine in over 25 years. ATP 3-72, Operations in a Nuclear Environment provides guidance on how to plan for tactical-level operations in a nuclear environment. This guide highlights, by warfighting function, what considerations are useful in preparing for and continuing operations in a nuclear environment. A basis of departure for the Army's leader development enterprise, this guide enables development of professional military education and staff training that enables leaders at the tactical level to develop understanding of the well-characterized nuclear environment. The Army reformed its PME rapidly in the face of emerging improvised explosive device threats during Operations IRAQI FREEDOM and ENDURING FREEDOM. It must do so again to address this threat.

At the tactical level much of the information needed to operate in a nuclear environment already exists in available doctrine and within enablers spread across the force. ATP 3-11.32, CBRN Passive Defense, provides critical tactical level guidance for Soldiers and leaders to understand the nuclear environment and protect themselves from its effects. CBRN Soldiers, Warrant Officers, and Officers should also be recognized as a valuable source of information and advice for leaders when developing and executing training and planning and conducting operations. Other references can be found at the end of the article that provide more information on tactical and operational planning considerations.

These resources provide leaders with the knowledge needed to prepare their forces for the nuclear environment. Yet this information has long been available. The crux of the problem remains the prioritization of nuclear training against the many competing requirements units face today. Given the threats presented by our strategic rivals and the degrading international security environment, it is time to ensure that nuclear training makes it above the cut line. This does not necessarily have to come at the expense of other important training. Other than basic classroom instruction, nuclear training should be integrated throughout other training events and exercises that train a unit's mission essential tasks. An infantry or armored formation should still train its offensive and defensive tasks, but some iterations should include the threat of nuclear attack or operating in a contaminated environment. Sustainment units should train sustainment tasks in a contaminated environment. Medical personnel should train to treat radiological casualties with both radiological and traditional injuries.

Nuclear effects are best thought of as an enemy-produced threat environment that must be accounted for in operations against a nuclear-armed adversary. Fortunately, units are already equipped to do this. While much of the nuclear equipment issued to units may be dated, it is nonetheless sufficient for understanding and assessing a radiological environment and protecting personnel and equipment. Priority should be placed on ensuring personnel are trained to operate in the equipment, and leaders must ensure this equipment is fully mission capable. There are many organizations available for assistance in implementing change. The U.S. Army Nuclear and CWMD Agency, Defense Threat Reduction Agency, and Maneuver Support Center of Excellence all have expertise and training available for the joint force. Leader involvement in incorporating nuclear environments into training and exercises is the most responsible way to address this threat while ensuring unit training is not myopically focused on this one threat.

Closing Thoughts

The strength of the U.S. military has always been its people. To prepare those people to win the Nation's wars has been the burden of Army leaders since its inception. Today, as perhaps never before, the Army is faced with challenges across all domains, some much more likely than so-called limited nuclear war. Prioritizing resources to prepare our forces to mitigate risk to mission is paramount – we must be balanced in our approach. Preparing Army leaders through our core competencies is not only a responsible, low-cost way to mitigate risk, it relies on our people – our adaptive, agile leaders that demonstrate every day that the Army is ready to fight and win.

Figure 5. Active duty military personnel simulate an attack out of their foxholes immediately following a nuclear detonation in the 1950s DESERT ROCK nuclear tests. Source: Military.com

The nuclear battlefield is not insurmountable and deterring nuclear-armed adversaries from making it a reality is not limited to the nuclear operations performed by the Army's great sister services. A multi-domain operations ready Army must be prepared to meet the challenges of the modern battlefield, to include one that includes nuclear use. Adaptability is the Army's greatest strength, and it must adapt to this known threat.

Recommended Resources:

ATP 3-11.36 CBRN Planning (09/09/2021)

ATP 3-11.37 CBRN Reconnaissance (03/31/2021)

ATP 4-02.83 Treatment of Nuclear and Radiological Casualties (05/05/2014)

FM 3-11 CBRN Operations (05/23/2019)

TM 3-11.32 CBRN Warning and Reporting (12/21/2017)

TM 3-11.91 CBRN Threats and Hazards (05/14/2021)

Endnotes

1. Jim Mattis, National Defense Strategy, Washington, DC: U.S. Department of Defense, 2018 https://dod.defense.gov/ [1] Definitions vary, and more can be found in Carus, W. Seth, Occasional Paper #8, Defining “Weapons of Mass Destruction”, published by the Center for the Study of Weapons of Mass Destruction, January 2012.
2. [2] As defined in the Treaty on the Non-Proliferation of Nuclear Weapons.
3. [3] The authors use the term “non-strategic nuclear weapons” to characterize those nuclear weapons delivered by systems not defined in the New START II treaty between the US and Russian Federation (heavy bombers, inter-continental ballistic missiles and submarine-launched ballistic missiles). While some authors prefer the use of “tactical” to “non-strategic”, there is no scenario in which nuclear weapons will not have effects beyond the tactical level of war as the strategic implications of even nuclear weapons testing would be significant.
4. [4] Dual-capable systems are those with the capability to deliver either conventional or nuclear payloads. [5] Counterforce is the idea, introduced by Secretary of Defense Robert McNamara in 1962, that “[P]rincipal military objectives… should be destruction of the enemy’s military forces, not of his population….” [11]
5. [6] More information about USANCA’s efforts to modernize Army LDT&E can be found in the article Keeping Me Awake at Night: The Coming Nuclear and WMD Battlefield and the Urgency to Improve Army Readiness, CWMD Journal 23rd ed., U.S. Army Nuclear and Countering WMD Agency, Fort Belvoir, Jan 22.
6. [7] Nuclear weapon effects that are predominate within the first minute after the detonation are referred to as “initial” nuclear weapon effects. Those following, to include fallout, are referred to as “residual”.
7. [8] Maneuver Support Center of Excellence, ATP 3-72/MCRP 10-10E.9/NTTP 3-72.1/AFTTP 3-2.65 Multi-Service Tactics, Techniques and Procedures for Operations in a Nuclear Environment, Fort Eustis: Training and Doctrine Command, 2022.
8. [9] Defined in Title I of the Atomic Energy Act of 1954 as including plutonium-239, uranium-235 and uranium-233.
9. [10] The U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency (USANCA) delivers the Theater Nuclear Operations Course to audiences DoD-wide. For more information on this course, and many other offerings in CWMD education, you can find the Defense Nuclear Weapons School catalog at https://dnws.dtra.mil.

Notes

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Considerations of Emerging Technologies on Weapons of Mass Destruction

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Introduction

The rise of emerging technologies changes the threat landscape on a near-daily basis. With the return to great power competition, Russia and China continually modernize their capabilities while conducting research and development on emerging technologies. The 2018 National Defense Strategy describes the current complex security environment defined by "rapid technological change" and "challenges from adversaries in every operating domain."[1] Technological developments have profoundly affected the strategic and operational WMD environment and increased the reach, tempo, and effectiveness of systems that weaken strategic deterrence and make conflict involving WMDs more likely. The following is a brief overview of recent significant technological developments to include intermediate-range missiles, hypersonic delivery systems, unmanned systems and artificial intelligence (AI), and continuing advances in biotechnology in order to reinforce the need to reenergize the United States' commitment to modernization.

Cyber Weapons

Cyber weapons can disable or disrupt adversary WMD programs as a counter-proliferation tool. The 2010 Stuxnet attack on an Iranian uranium-enrichment facility is a case in point. Stuxnet was a form of malware designed to spread across the globe from one computer to the next and unleash its payload only when it entered an industrial control system (ICS) with the characteristics of Iran's uranium-enrichment facility at Natanz.[2] Once inside, it altered the system's program to monitor and regulate the supersonic spin of centrifuges that led them to become unstable and ultimately breakdown. The attack demonstrated the ability of cyber weapons to penetrate an adversary's development of WMD.

Stuxnet, a 500 kilobyte (KB) computer worm, infected the software of at least 14 industrial sites in Iran, including the uranium-enrichment plant at Natanz.[3] While a computer virus relies on an unwitting victim to install it, a worm spreads on its own, often over a computer network. Stuxnet used four "zero-day" exploits to conduct its attack.[4] A zero-day exploit is, at its core, a flaw. It is an unknown exploit that exposes a vulnerability in software or hardware and can create complicated problems well before anyone realizes something is wrong.[5] The weapon was designed to manipulate computer systems made by the German firm Siemens that control and monitor the speed of the centrifuges. The goal of the worm in a Windows computer was to search for Siemens Step 7 software, a type of software used to program and monitor Programmable Logic Controllers (PLCs)

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primarily used in ICS in critical infrastructure.[6] If Stuxnet did not find the Step 7 software in the infected Windows machine, it remained dormant and harmless. Since the computers at the Natanz plant were air-gapped (not connected) from the internet, they could not be reached directly by the remote attackers.[7] So the attackers designed their weapon to spread via infected USB flash drives using the Windows auto-run feature. The sophistication of the attack led many to believe that Stuxnet was the creation of a state-level sponsored attack conspired by the U.S. and Israel although attribution was never officially finalized nor acknowledged.

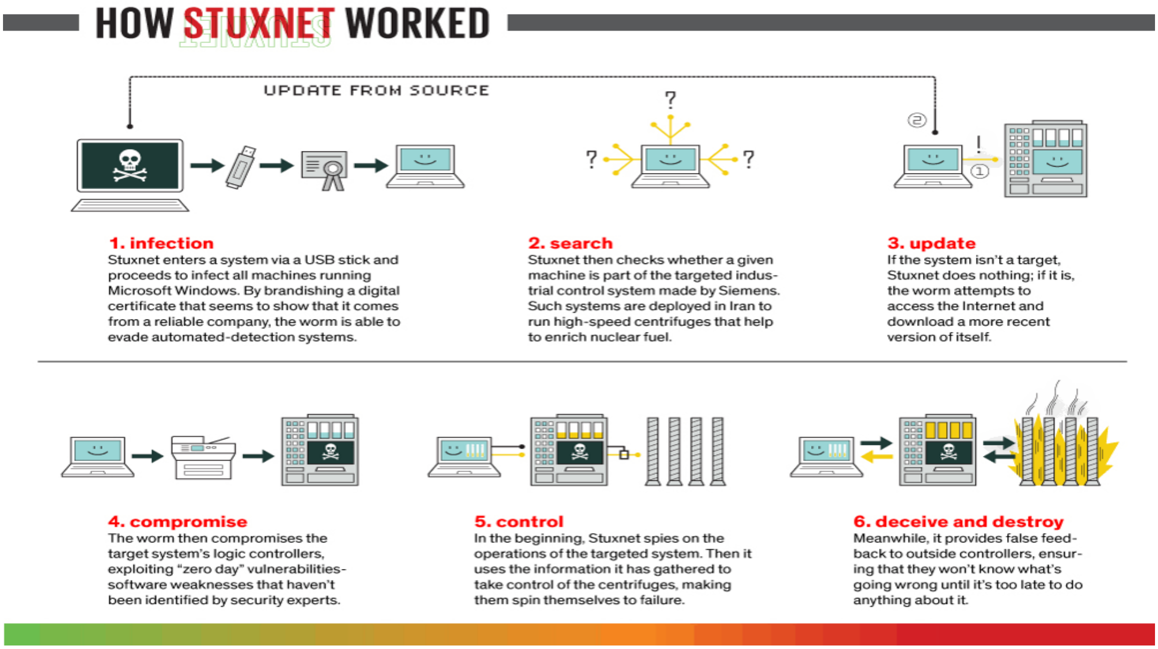

Figure 1. How Stuxnet Worked[8]

Recent reports highlight potential cyber vulnerabilities in the U.S. nuclear command, control, and communication (NC3) system that enables early warning, timely, and deliberate decision making.[9] All nuclear-armed states likely face similar challenges; these challenges are not unique to the United States. The possibility of a cyber attack on U.S. NC3 systems raises concern among experts that such cyber attacks could weaken strategic deterrence and make nuclear conflict more likely.[10] For example, cyber attacks on the U.S. NC3 could degrade its deterrence effect and embolden an adversary during a nuclear standoff posing critical escalation risks. Any state that fears its nuclear forces are at risk to cyber attacks might have incentives to use them early in a crisis because waiting could put it at a grave disadvantage.[11] Knowing this, third parties looking to incite escalation between opponents could then spoof an adversary's NC3 during a crisis to make it appear as though it is under attack by the other. Additionally, some NC3 capabilities are dependent on dual-use platforms such as sensory and communications satellites.[12] Cyber attacks on those systems could unintentionally appear as an attack on the other's strategic deterrent. These types of concerns are already being discussed and addressed among CWMD experts within the U.S. nuclear enterprise, academic, and think tank communities.[13]

Cyber attacks have grown in recent years and will continue to grow as Russia and China enhance their cyber capabilities and organizations. Russian cyber units include the GRU's Advanced Persistent Threat (APT) 28, Fancy Bear, Voodoo Bear, Sandworm, Tsar Team, Unit 26165, Unit 74455, and Unit 54777; Foreign Intelligence Service's (SVR) ATP 29, Cozy Bear, and the Dukes; and the Federal Security Service's (FSB) Berserk Bear, Energetic Bear, Gamaredon, TeamSpy, Dragonfly, Havex, Crouching Yeti, and Koala.[14] The most significant Chinese cyber units include Units 61398 and 61486.[15] Such organizations have proven their advanced cyber capabilities by through successful cyber attacks on critical infrastructure, financial, and medical organizations worldwide.

Ground-Launched Ballistic/Cruise Missiles (GLBM/GLCM) and the withdrawal from the Intermediate-Range Nuclear Forces (INF) Treaty

The 1987 Intermediate-Range Nuclear Forces (INF) Treaty required the U.S. and the Soviet Union to eliminate and permanently disable all of their nuclear and conventional ground-launched ballistic and cruise missiles with ranges of 500 to 5,500 km.[16] The treaty marked the first time the superpowers had agreed to reduce their nuclear arsenals, eliminate an entire category of nuclear weapons, and employ extensive on-site inspections for verification. As a result of the INF Treaty, the U.S. and the Soviet Union destroyed a total of 2,692 short, medium, and intermediate-range missiles by the treaty's implementation deadline of 01 June 1991.[17]

Missile Deployments Eliminated by the INF Treaty

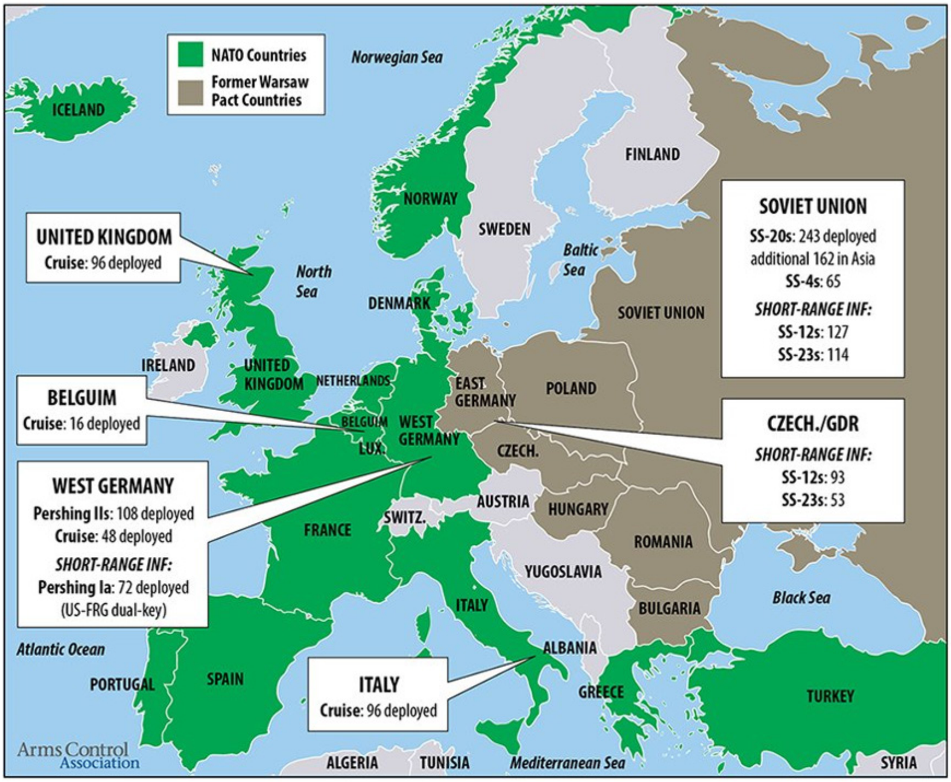

Figure 2. Missile Deployments Eliminated by the 1987 INF Treaty[18]

However, Russia raised the possibility of withdrawing from the INF Treaty since the mid-2000s.[19] Russia argued that the treaty unfairly prevented it from possessing weapons that its neighbors, such as China, were developing and fielding.[20] Russia also suggested the proposed U.S. deployment of strategic anti-ballistic missile systems in Europe might trigger a Russian withdrawal from the treaty, presumably so Moscow could deploy missiles targeting any future U.S. anti-missile sites. Still, the U.S. and Russia issued a statement on 25 October 2007 at the United Nations General Assembly reaffirming their "support" for the treaty and calling on all other states to join them in renouncing the missiles banned by the treaty.[21]

Reports began to emerge in 2013 and 2014 that the U.S. had concerns about Russia's compliance with the INF Treaty. In July 2014, the U.S. State Department found Russia to be in violation of the agreement by producing and testing an illegal ground-launched cruise missile.[22] Russia responded in August 2014 refuting the claim. Throughout 2015 and most of 2016, U.S. Defense and State Department officials had publicly expressed skepticism that the Russian cruise missiles at issue had been deployed. But an 19 October 2016, report in The New York Times cited anonymous U.S. officials who were concerned that Russia was producing more missiles than needed solely for flight testing increasing fears that Moscow was on the verge of deploying the missile.[23] By 14 February 2017, The New York Times cited U.S. officials declaring that Russia had deployed an operational unit of the treaty-noncompliant cruise missile now known as the SSC-8.[24] On 08 March 2017, General Paul Selva, the vice chairman of the U.S. Joint Chiefs of Staff, confirmed Russia had deployed a ground-launched cruise missile that “violates the spirit and intent” of the INF Treaty.[25]

The 2018 U.S. State Department’s annual assessment of Russian compliance with key arms control agreements asserted Russian noncompliance with the INF Treaty. The report declared the missile in dispute was distinct from two other Russian missile systems, the R-500/SSC-7 Iskander GLCM and the RS-26 ballistic missile.[26] The R-500 has a Russian-declared range below the 500 km INF Treaty limit, and Russia identifies the RS-26 as an intercontinental ballistic missile treated in accordance with the New Strategic Arms Reduction Treaty (New START). The report also appeared to suggest the launcher for the allegedly noncompliant missile is different from the launcher for the Iskander.[27] In late 2017, the U.S. for the first time revealed both the U.S. name for the missile of concern, the SSC-8, and the apparent Russian designation, the 9M729.

Congress for the past several years has urged a more assertive military and economic response to Russia’s violation. The 2018 National Defense Authorization Act (NDAA) authorized funds for the U.S. Defense Department to develop a conventional, road-mobile, ground-launched cruise missile that, if tested, would violate the treaty.[28] The 2019 NDAA also included provisions on the INF treaty. Section 1243 stated that no later than 15 January 2019, the president would submit to Congress a determination on whether Russia was “in material breach” of its INF Treaty obligations and whether the “prohibitions set forth in Article VI of the INF Treaty remain binding on the United States.”[29] Section 1244 expressed that in light of Russia’s violation of the treaty, the U.S. is “legally entitled to suspend the operation of the INF Treaty in whole or in part” as long as Russia is in material breach. For FY20, the Defense Department requested nearly $100 million to develop three new missile systems that exceed the range limits of the INF treaty. After repeatedly denying the existence of the 9M729 cruise missile, Russia has since acknowledged the missile but denies that the missile was tested or the range is within the limits of the INF Treaty.[30]

On 02 February 2019, President Trump and Secretary of State Pompeo announced that the U.S. suspended its obligations under the INF Treaty and will withdraw from the treaty in six months if Russia did not return to compliance.[31] Shortly thereafter, Russian President Vladimir Putin also announced that Russia was officially suspending its treaty obligations. On 02 August 2019, the U.S. formally withdrew from the INF Treaty. In a statement, Secretary Pompeo said, “With the full support of our NATO Allies, the United States has determined Russia to be in material breach of the treaty, and has subsequently suspended our obligations under the treaty.”[32] He declared that “Russia is solely responsible for the treaty’s demise.” A day later, U.S. Secretary of Defense Mark Esper said that he was in favor of deploying conventional ground-launched, intermediate-range missiles in Asia “sooner rather than later.”[33]

The U.S. did not indicate what ground-launched INF-range missiles it will deploy and where it will deploy them but it does not plan to arm them with nuclear warheads.[34] In contrast China, which already fields nuclear as well as conventionally armed INF-range missiles, and Russia are expected to field a nuclear-armed version of the 9M729.[35] However, the U.S. decided to field sea-based nuclear missiles (low-yield warheads on submarine-launched ballistic missiles and sea-launched cruise missiles) in response to Russia’s growing force of theater-range nuclear weapons.[36]

The U.S. will develop and field conventionally-armed, ground-launched INF-range missiles principally to counter China’s and Russia’s anti-access/area denial (A2/AD) capabilities.[37] As well as being more cost-effective than air or sea-launched systems, they can be emplaced in range of their targets during peacetime and always stand ready for employment.[38] They are also more survivable than aircraft on the ground or ships in port if they are mobile and based in locations that afford large dispersal areas.[39]

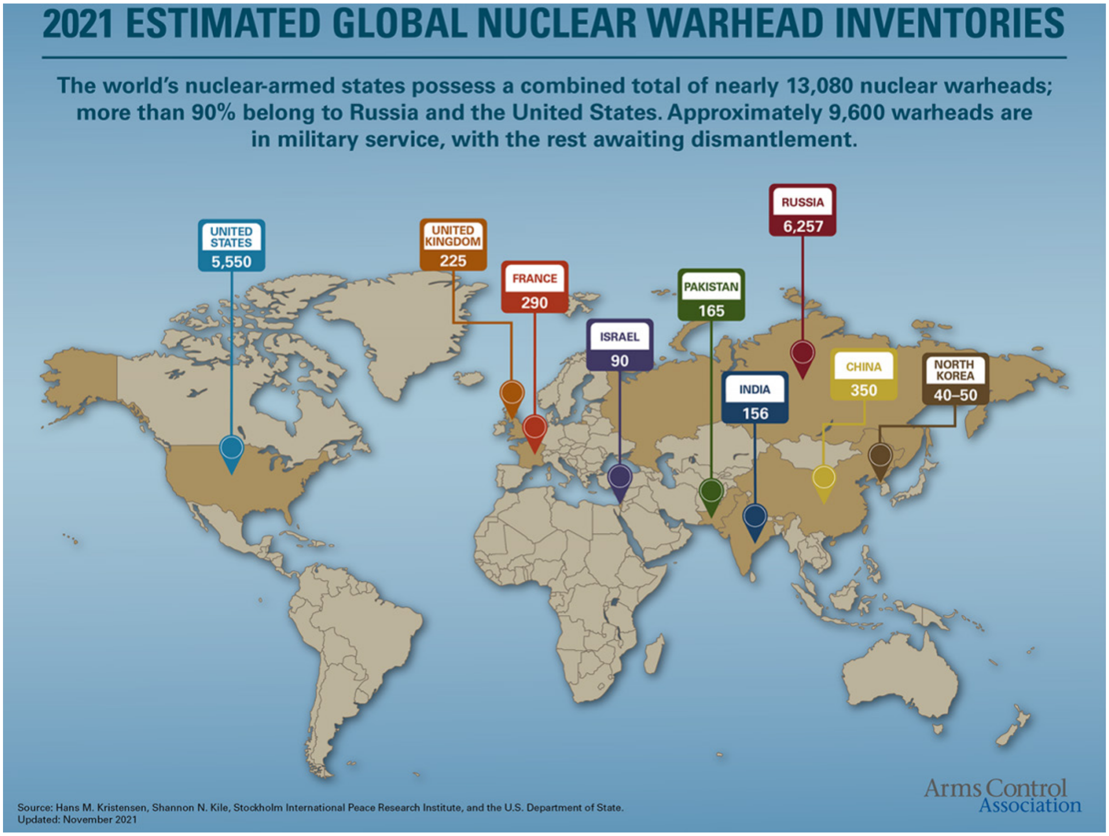

Figure 3. 2021 Estimated Global Nuclear Warhead Inventories[40]

Hypersonic Missiles

Hypersonic weapons systems operate at speeds greater than Mach 5.[41] Traditional long-range ballistic missile reentry vehicles travel at hypersonic speeds as well but lack maneuverability following a ballistic trajectory. Traditional cruise missiles are maneuverable but travel below hypersonic speeds. The emerging class of hypersonic vehicles are both fast and maneuverable.[42] They include hypersonic boost-glide vehicles (HGVs), which are launched by a rocket to an apex and then descend into the atmosphere where they use aerodynamic forces to glide at hypersonic speeds to their targets. Hypersonic cruise missiles (HCMs) are launched from a rocket or aircraft with a small solid rocket motor giving them enough velocity to propel them through the atmosphere at hypersonic speeds to their targets.[43] HGVs are similar to existing maneuvering reentry vehicles (MaRVs) for ballistic missiles to the extent they both exploit the ability to glide and maneuver in the atmosphere, but HGVs do so much earlier in their flight profile than MaRVs and with less predictability as to their target. HCMs could reach a target 1,000 km away within 10 minutes as compared to an hour for the Tomahawk cruise missile.[44]

The speed, altitude, and maneuverability of HGVs and HCMs make them almost impossible to defeat with existing air and missile defenses. They can travel below the intercept range of current mid-course missile defenses, like the Advanced Electronic Guided Interceptor System (AEGIS) or the Terminal High Altitude Area Defense (THAAD), and above that of air and point missile defenses, such as the Phased Array Tracking Radar to Intercept of Target (PATRIOT).[45] The U.S. is investing in a new space-based sensor layer to enable earlier tracking and more intercept opportunities of hypersonic missiles.[46] Other emerging capabilities, such as cannons or rail guns firing hypervelocity projectiles, directed energy weapons, and even space-based interceptors, may be part of future defenses against hypersonic missile systems.[47] Conventionally-armed hypersonic missiles with precision guidance have the potential to destroy or disable important elements of an adversary's critical military infrastructure which directly bear on both nuclear and conventional forces. The

U.S. is interested in conventionally-armed hypersonic missiles as a means to counter Chinese and Russian A2/AD capabilities.[48]

Unmanned Systems and AI

Unmanned systems are affording adversaries the means to deliver weapon payloads and conduct intelligence, surveillance, and reconnaissance (ISR).[49] For example, unmanned aerial systems have played a pivotal role in recent conflicts in Syria, northern Iraq, Libya, and Nagorno-Karabakh.[50] Unmanned systems, which frequently utilize AI, include unmanned aerial system (UAS), unmanned surface vessel (USV) or unmanned underwater vessel (UUV), and unmanned ground vehicles (UGV). While UASs and UUVs are more likely than other types of unmanned systems to deliver WMD payloads, it is not outside the realm of possibilities that any unmanned system could be utilized to do so. Russia currently is developing a UUV named Poseidon to deliver a nuclear warhead. Poseidon is the only publicly reported UUV intended to be used for WMD delivery.[51]

UASs could be outfitted with agricultural-type sprayers to disseminate chemical, biological, or radiological agents. UASs also could be flown directly into certain industrial targets (with or without explosive payloads) that could result in WMD-like effects (i.e. causing a release of toxic industrial chemicals (TICs) from a chemical plant or storage site).[52] UASs also tend to fly slower and at lower altitudes than the missiles targeted by current air and missile defense systems like PATRIOT.[53] To address the growing challenge of adversary UASs, the U.S. Defense Department invested at least $404 million on counter-UAS research and development and at least $83 million on procurement for FY21.[54]

As the technology improves to coordinate and integrate attacks involving multiple unmanned systems, the combined effect delivering small payloads will grow. In September 2019, Iran demonstrated how a coordinated en masse attack of UASs and cruise missiles could temporarily disable a large percentage of Saudi Arabia's oil processing infrastructure despite the proximity of PATRIOT air defense systems.[55] An en masse or swarm attack of UASs with chemical and biological payloads could have a potent impact. The U.S., China, and Russia are pursuing UAS swarm technologies.[56]

Unlike the hypersonic delivery vehicles discussed earlier, unmanned systems, in general, are being used by many state and non-state actors alike. There is a large and growing commercial market for small UASs accessible to all actors dominated by Chinese suppliers.[57] A 2017 analysis by the Institute for Defense Analyses of technological developments, projected small UASs would decrease in size while maintaining or even increase capabilities such as flight time, payload, range, endurance, and speed. Emerging capabilities, enabled by AI, robotic technologies, sensor technologies, and enhanced audio and video, are expected to become available and integrated.[58] As the capabilities of small commercial UAS grow, the use of these systems can only be expected to increase, potentially with WMD effect.[59]

Biotechnology

Many experts believe that the accelerating pace of progress in the biological sciences and greater awareness of the contributions made by biotechnology are changing the threat landscape in two ways: 1) new scientific developments are further reducing the technical barriers to the production and dissemination of biological weapons, including enabling the creation of new and even more dangerous biological agents; and 2) knowledge of biological systems particularly is growing, reflected not only in ever larger datasets of genomic information but in our ability to link that data to the biological processes associated with the pathogen-host interaction.[60] This could involve modification of known pathogens to enhance virulence and environmental stability or enabling an agent to nullify the effects of vaccines or other medical countermeasures. Recent discussions have focused on the impact of synthetic biology in general and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) gene editing. In its essence, "synthetic biology aims to improve the process of genetic engineering…where the design of genetic systems and the idiosyncrasies of DNA are decoupled, and one can compose living systems by mixing-and-matching genetic parts."[61] Synthetic biology is a subset of biotechnology focused on the modification of microorganisms or the creation of new ones and focuses on efforts to make genetic engineering more predictable by using standardized components, computer design, and conceptual approaches.[62]

CRISPR is a gene editing technology that allows easier and more precise modification of genetic material adapted from the system used by bacteria to defend against viral infections. The rapid development and exploitation of CRISPR surprised the national security community raising concerns that it enabled the creation of new biological warfare capabilities by both state and non-state actors.[63] The most systematic review of the national security implications of synthetic biology appeared in a 2018 report issued by a committee of the National Academies of Sciences, Engineering, and Medicine. According to the report, the most worrying advances relate to the ability to construct known pathogenic viruses from their genetic sequence, to produce dangerous biochemicals, and to modify known bacteria.[64] For example, COVID-19 could be genetically modified to create a variant even more contagious and resistant to vaccines.

Conclusion

The strategic environment is becoming more complex and unpredictable. A broader range of weapons systems, both nuclear and non-nuclear, theater and intercontinental, increasingly will bear on strategic balances and stability. The U.S. must remain at the forefront of developing, utilizing, and understanding the national security implications of emerging and disruptive technologies such as intermediate-range missiles, hypersonic delivery systems, unmanned systems and AI, and continued advancements in biotechnology. These technologies dramatically impact the character of conflict, nation's economic welfare, and tip the scales of great power competition. It is critical the U.S. is prepared for the next pandemic and apply lessons learned from the COVID-19 response. Emerging and disruptive technologies will have both stabilizing and destabilizing impacts on the development, acquisition, and use of WMD.

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There's no way out of here?

The Army's lasting challenge with nuclear weapons

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For more than 30 years the Army has tried to overlook the potential of nuclear weapons use on the battlefield. The ending of the Cold War allowed the Army to divest its nuclear delivery capability and shift operational emphasis to combined arms and other operational and challenges. Combined with a reduced budget and directed low-intensity or peace enforcement missions, preparing to operate in a nuclear (or other CBRN environment) was reduced in priority. Intervening Army operational experience in the Balkans emphasized security and stability operations and after 9/11, a shift to primarily tactical engagement of terrorist and insurgents in a COIN environment. Other than exploitation of Iraqi WMD programs, CBRN Defense was relegated to small Army communities (Army Chemical Corps, Functional Area 52 Officers and Health Physicists) focused on the Counter WMD mission within the SOCOM operational environment and preparations for possible employment on the Korean Peninsula. The notion of near peer adversaries, large scale combat operations and the related challenges was left fallow until the 2014 Russian invasion of Ukraine and the continued expansion of Chinese power projection in the South China Sea began to force changes in Army thinking. The emerging strategic picture shows Russia and China as the near-peer adversaries (Russian operational and tactical challenges in Ukraine notwithstanding), both armed with nuclear weapons and the next two included adversaries (North Korea) in possession or rapidly pursuing (Iran) nuclear weapons. It is clear the Army must acknowledge that adversary nuclear weapons are a reality and assuming that international norms and treaties restricting their use are quaint notions that no longer present the barrier they were intended to provide. In that acknowledgment, the Army must undertake clear thinking on how adversary nuclear weapons impact operational and tactical planning and execution, and what Army units and leaders must do to train and prepare. Have the changes in adversary been enough to alter the Army's thinking on nuclear weapons?

Battlefield nuclear weapons[1] use poses a unique operational challenge which is difficult to reconcile with past experience-there isn't any- and allow for future conceptual planning. Accepting the notion of battlefield nuclear weapons and indeed potential use of any CBRN weapons have represented a continued failure of imagination by the Army. This failure is borne of a baseline belief that their use is significantly norm breaking enough that potential adversaries will 'do a lot of things but won't do that'. This intellectual blind spot has left the Army unable to fully articulate how it prepares and might deal with nuclear weapons effects or operate in post-nuclear detonation environment. This organizational lack of interest in the post nuclear detonation operating environment has also encouraged atrophy of the intellectual capacity development needed to ensure the Army

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can, if needed "fight dirty". Simply positing that because nuclear weapons are a "game changer" and their use will imply an immediate cessation of operations is a casual position to take when the two most likely peer adversaries are amply armed with nuclear weapons. In addition, assuming that there is some line an adversary will not cross or threshold the Army can operate below- and ensure no nuclear weapons use- is somewhat wishful and assumes our adversary has the same lines and view of the operational situation.

The Army needs to take two steps in the near term to more adequately acknowledge the role of nuclear weapons in the 21st Century. First, Army leaders must re-institute the study and institutional understanding of deterrence theory and how the application of conventional force may equate to a deterrent effect against a nuclear armed adversary. Second, the Army must force itself to undertake the intellectual struggle to (re)develop concepts and practices for dealing with nuclear weapons use in a future operational environment. Although there is a small material component to these two steps- the major thrust is intellectual, the Army must revisit its work in the late 1970s and early 1980s to understand how the Army expected nuclear weapons use on the battlefield to impact operations, review how the Army expected to deal with such use and pull forward the - still relevant - ideas and apply them to ongoing, professional education, concept development and force design.

Wishing the problem away.

"Neither the U.S. nor adversaries will employ nuclear weapons. The use of such weapons would so significantly alter the strategic context that different operational approaches would be required. (This assumption does not mean that this concept ignores the threat of nuclear weapons. Army forces must be resilient against all possible forms of attack. Furthermore, commanders will have to account for the possibility of nuclear attack in formulating schemes of maneuver and accounting for the risk of escalation that might lead to operational restrictions on where and how the Joint Force operates."[2]

The passage above clearly articulates the Army "wish" about the conflict it would like to fight, even with the "catch all" follow on thoughts. In other contexts, the notion of "thresholds" has been suggested to delineate some theoretical line below which Army operations will occur and not have an adversary consider nuclear weapons use. This entry argument for nuclear weapons use makes a large assumption on the part of both our nuclear armed adversaries. Rather than assume "not at all", perhaps a better assumption would be that nuclear armed adversaries "may employ nuclear weapons, although those conditions are difficult to estimate." The Army's strategy and futures program could then assess what operational conditions might exist that compel our nuclear armed adversaries to consider nuclear weapons use and with what intended operational effect. This intellectual effort would then inform training and education areas to ensure Army leaders at all levels have thought through the needed counter measures of nuclear weapons use and effects. Most importantly, Army leaders must accept the intellectual and institutional reality that nuclear armed adversaries are not able to be set aside from the Army's preferred operational model.

There is no doubt that the Army's modernization challenges are significant, following on from nearly 20 years of counter-terrorism and counter-insurgency type operations. The need to shift back to combined arms fire and maneuver warfare against a near-peer adversary brings any number of large challenges across the DOTMLPF (Doctrine, Organization, Training, Material, Leadership, Personnel, and Facilities) spectrum. The Army is now in the intellectual space equivalent to the late 70s: post-conflict, budget constraints, technologically developing adversary (now two instead of just one), emergent forms of technology impacting warfare; multiple global security issues. A major part of the Army's post –Vietnam recasting was to take a clear-eyed look at what the battlefield might look like, the result of this effort was what eventually became known as AirLand battle. This work to better understand the future operational environment is ongoing across the Army and should incorporate the dynamics of a conventional conflict with a nuclear armed adversary. Not only should the Army review its work form the 70 and 80s on the operational challenges of conventional and nuclear operations, an even earlier time period also can provide a reference point:

"A great institution like the Army always is in transition. And though the character of reform

isseldom as profound as the claims of senior leaders or the Army Times may suggest, in the 1950s change often matched the hyperbole of its advocates. The Army found itself grappling for the first time with the perplexing implications of nuclear warfare, seeking ways of adapting its organization and doctrine to accommodate rapid technological advance; and attempting to square apparently revolutionary change with traditional habits and practical constraints of the military art."[3]

The Army's Pentomic division experiment was the last major doctrinal and organizational effort to enable operations in a nuclear environment. Later efforts via AirLand battle doctrine recognized the challenge and brought forth the idea of decentralized and dispersed operations. However, AirLand Battle was also focused on shifting Army thinking to the operational level and defeat of new Soviet ground capabilities and tactics. In both cases the Army accepted nuclear weapons use as part of the operational environment and part of the adversaries' capability. When and where they would be used was the subject then- as now- of much discussion and debate. The debate, however, is important and more helpful to allow Army unit leaders to better understand the risk in time and place that adversary nuclear weapons may pose. Simply un-acknowledging them is not helpful and signals to the Army (and our adversaries) that we don't take the hazard seriously.

Where to go from here?

There is a joke about acknowledging a problem. In this case Army leaders must acknowledge the threat of nuclear weapons (and other WMD) in the operational environment and not caveat them as capability in being- available to our adversaries but not ever useable. This acknowledgement must also come in the context of the current adversaries which have established and improving nuclear weapons programs and capabilities. That acknowledgement must be accompanied by a more deliberate effort to incorporate nuclear weapons into operational planning, exercising and training. Although there already many "campaigns of learning" ongoing, the Army must re-elevate the notion of deterrence as a topic in Professional Military Education. Specifically, Army leaders must understand land forces role in deterrence especially as the Nuclear Posture Review process reviews the notion of integrated deterrence. The centrality of deterrence can then enable broader thinking about our adversaries' capabilities and how they may be employed in the future operational environment. For nuclear weapons more specifically, the Army has begun to implement a program known as Conventional-Nuclear Integration (CNI) which will facilitate training, exercise and education opportunities to re-acquaint the force with nuclear weapons effects and how they may impact and operational force, and how operational and tactical missions can still occur. CNI and the Army FA 52 community will also work to develop exercise and training concepts to include nuclear weapons into existing exercise programs. This work will be done to preclude the notion that nuclear weapons use equates to a full stop of all operational activity in expectation of something else happening that is beyond the control of the Army or its unit leaders. Finally, the Army must continue to demonstrate its willingness and capability to operate in and through nuclear hazards, in other words be willing to "fight dirty."

Across the DOTMLPF construct, the Army's focus within the training and leader education areas can address this shortfall quickly and most effectively. In the training and leader education areas acknowledgement of the nuclear threat of our main potential adversaries is a needed starting point. Concurrently, that acknowledgement cannot then wish away the possibility of nuclear weapons use in a future conflict with a passing and convenient assumption. Acknowledgment can then stimulate intellectual energy to ensure the Army can establish and maintain basic skills needed to prepare and operate in a post-detonation operational environment. On the material side, confirming funding for upgrades and procurement of modernized radiation detection systems will ensure Army forces are able to accurately detect and characterize radiological hazards. Along with detection, nuclear survivability of new equipment under development by capability developers must return to incorporation of nuclear effects hardening. These upgrades and procurement are comparatively low costs and provide the Army with a modernized radiation detection and monitoring capability. In sum, Army Modernization must incorporate the nuclear threat.

Conclusion

The Army must be willing to set aside its institutional priors and reset its intellectual baselines about nuclear weapons. Nuclear armed adversaries in a future conflict may not operate with the restraint we would wish or expect. When thinking about our potential adversaries armed with nuclear weapons, we should perhaps believe they might in fact use them. An in-depth assessment of the current Russian invasion of Ukraine may be illustrative in how a nuclear armed adversary may operate in the future. As the Army continues its shift to large scale combat operations, incorporation of nuclear weapons effects to operational constructs and in training and exercise venues will ensure a more fully prepared Army. In addition to the intellectual reemphasis on deterrence, the Army can more fully assess and consider the future operational environment with a clear consideration of adversaries full capabilities. Simply focusing on the "hoped for" warfight the Army would prefer based on its capabilities and strengths and without full consideration of the adversary "vote" may leave the Army at an operational and intellectual disadvantage in competition, crisis and conflict.

Notes

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Air Force Strikes and Army Fires: Innovation and Long-Term Competition for the Joint Force

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Against the backdrop of increasing provocations from China in the Pacific and Russia in eastern Europe, the Department of Defense (DoD) faces its own internal confrontation between the Air Force and the Army over the Army's Long-Range Precision Fires program. The Long-Range Precision Fires program, the Army's top modernization priority, seeks to field new capabilities to outrange and outshoot U.S. adversaries and enable multi-domain superiority for the Army and the Joint Force.[1] The Army's Long-Range Precision Fires program represents an important investment in sustaining military innovation to enhance U.S. standoff warfare capability while keeping pace with China and Russia's capabilities. However, Air power advocates warn that the effort crowds the long-range strike mission, a mission that some believe belongs strictly to the Air Force. "Jointness," they argue, should prohibit the Army from competing with the Air Force to provide long-range strike to the Joint Force.[2] This interpretation of jointness stymies military innovation at the very time the DoD needs its most. Moreover, competition between the Air Force and Army around long-range precision strike capabilities may drive the development of more innovative, lethal, and cost-effective technologies. The battle between the Air Force and Army over long-range strike capabilities presents a case study for military innovation and a model for how the Joint Force should prepare and procure to win in the era of strategic competition.

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Military Innovation and Modern Warfare

Military strategists define "military innovation" as a substantial change in military operations – technology, doctrine, or organization – that significantly improves effectiveness in battlefield operations.[3] Military innovation is not about game-changing technology, but rather changing the game. For example, throughout the 20th and 21st centuries, standoff warfare enabled by long-range, high-tech precision fires has become increasingly central to the American way of war.[4] Originally devised to match the Soviet Union's overwhelming conventional forces, modern standoff warfare – the "Second Offset" – results from innovations in precision guided weapons technology as well as new operational concepts that emphasized seeing, targeting, and quickly debilitating adversary forces over movement and maneuver on the battlefield.[5]

Considering the future of warfare, some scholars of modern military strategy conclude that the very nature of war has changed, the result of further innovations in technology and military operational art.[6] The outcome of assured nuclear retaliation, emerging and disruptive technologies, and the increasingly interconnected nature of global affairs, this new age of warfare will be dominated by cyber warfare, information operations, and grey-zone activities – military and non-military operations below the level of arms conflict.[7] China and Russia's military strategies anticipate this evolution in warfare – in fact, they are driving it. China's leadership has elevated the concept of "intelligentization" as the guiding principle for its military strategy, with which it seeks to revolutionize their entire approach to warfighting and reshape the boundaries and rules of warfare.[8] Russia actively conducts cyber operations and information warfare campaign against Western allies and states in its near broad.[9] Nonetheless, China and Russia are each hedging for a future in which hard power is still dominant and central to U.S. global leadership.

For at least a decade, the development of capabilities and strategies that exploit regional asymmetries of force has been the focus of America's competitors and adversaries, who seek to maintain military advantage in theater long enough to seize their objectives.[10] Among these are anti-access, area denial (A2/AD) technologies and strategies that challenge U.S. military access and operations in every warfighting domain. Following careful study of U.S. military strategy, China's national and military leaders devised a counter-intervention strategy specifically aimed at weakening U.S. global influence by impeding force projection. China's maritime strategy seeks to disrupt free navigation in the South China Sea to challenge U.S. naval power projection and induce doubt among the United States' Pacific allies in its assured response to security threats in the region.[11] To strengthen its capability to deter potential adversaries and disrupt their combat operations, China launched a military modernization program to expand its nuclear arsenal and develop long-range precision strike systems, sophisticated space and counter-space technologies, and cyber-attack capabilities aimed at deterring and disrupting adversaries from adversary intervention in local conflict. China reinforces its anti-access strategy through legal claims denying military activity within in its exclusive economic zones and disputes with neighboring states to expand its territory.[12]

While China's counter-intervention strategy threatens U.S. influence and access in the Pacific, Russia presents significant challenge to U.S. force projection in Eurasia. Through its increasingly aggressive actions, Russia seeks to divide and weaken Western alliances and destabilize the European security order, undermine U.S. influence, and challenge international norms that favor democracy and the rule of law.[13] Russia has significantly upgraded and expanded its military capabilities, making it incredibly costly, if not impossible, for the United States and allies of the North Atlantic Treaty Organization (NATO) to intervene in security crises between Russia and member states. Unlike China, however, Russia does not aim solely to contest U.S. access to the region nor restrict Western forces' freedom of operations: rather, Russia expects to face adversaries in theater. Russian military strategy seeks to deny adversaries a quick and decisive victory by disrupting their concepts of operation, weaking their political resolve, and imposing high enough costs to force de-escalation.[14] Additionally, experts of modern military strategy assess that China or Russia will likely employ weapons of mass destruction (WMD) in a theater fight with the United

States and its allies to contest U.S. access to the theater or terminate the conflict on their terms.[15] This drives the urgent need for new and innovative capabilities to deter and – should deterrence fail – win against near-peer powers.[16]

Friendly Competition: Air Force Strikes and Army Fires

The Army's Long-Range Precision Fires program plans to deliver a portfolio of long-, intermediate-, and short-range cannons and surface-to-surface munitions by 2023 – a mix of capabilities to provide joint and service commanders more options to address the daunting challenges presented by Russia and China's layered A2/AD capabilities.[17] However, many air power proponents denounce the program, calling it an "encroachment" on the Air Force's long-held roles and missions. They call for the Army to abandon efforts to develop capability they say is duplicative to the Air Force's penetrating bombers and stand-off strike aircraft.[18] This criticism is grounded more in parochialism than a responsibility to the Joint Force and the Air Force's "core competencies."[19]

While the long-range strike mission has, for the last generation, belonged principally to the Air Force, this division of warfighting capabilities results more from nuclear arms control policy than military doctrine or technological capability. The Intermediate-Range Nuclear Forces (INF) Treaty signed by Russia and the United States in 1987 banned ground-launched conventional and nuclear missiles with ranges between 500 and 5,000 kilometers, artificially constraining standoff strike to air- and sea-launched systems.[20] With the signing of the INF treaty, the Army abandoned the Pershing II, the Army's ground-based medium-range ballistic missile that was central to U.S. posture against the Soviet Union during the 1980s.[21]

Figure 1. Several Pershing II missiles are prepared for launching at the McGregor Range Complex, New Mexico, on December 1, 1987. (Photo by Frank Trevino/DoD)[22]

The United States' withdrawal from the INF Treaty in 2019 lifted restrictions against ground-based long-range strike capabilities and presented the Army with renewed opportunity for innovation in doctrine and technology to meet the challenges of modern warfare against near-peer adversaries. Furthermore, the Army maintains that its Long-Range Precision Fires complement rather than complete with the Air Force and Navy's capabilities.[23] Similar to the Navy's concept for distributed military operations, the Army's modernization of its long-range precision fires is critical to addressing the multi-domain military problem posed by China and Russia.[24] In the face of such adversaries, overlapping service capabilities are not superfluous; rather, they are operationally necessary to provide joint and service commanders with a range of options and resilient capability against the military problem posed by China and Russia.[25]

Interservice Rivalry: The Engine of Military Innovation and Industry

Analyses of historical examples reveal that military innovation rarely happens organically; rather, civil and military leaders who recognize the need for change leverage intraservice politics, induce competition between military branches, and steer organizational culture to realize a new way of warfare.[26] Throughout military history, rivalry among the services for roles, missions, and capabilities has been a predominant factor driving military innovation. For example, military strategists and scholars of military innovation assess that competition between the Air Force and Navy during the Cold War drove the United States to expediently define submarines as the secure leg of the nuclear triad. Without interservice competition, the United States would likely undergone the time consuming and costly process of iterating through potential combinations of land-based and air-launched missiles powered by liquid and solid fuel – and may never have arrived at a submarine-based solution at all.[27] The Army's pursuit of long-range precision strike capabilities taps into this key driving force of military innovation – interservice rivalry.

Competition among the services is also a crucial element for the defense industrial base – how the nation mobilizes its economic power for deterrence and war. Economic theory demonstrates that competition for buyers drives innovation, improvements in performance, lower costs, and greater variety of capabilities. When the services compete for roles and missions, they operate as multiple autonomous buyers within the market for defense innovation, driving competition among government contractors and facilities to build capabilities that meet the requirements of each service's envisioned solution. When the DoD procures jointly, it operates as a single buyer within the defense market, denying market competition vital to a healthy and dynamic defense industrial base.[28]

Driving Military Innovation in the Era of Strategic Competition

In the era of strategic competition against China and Russia, the DoD's framework of jointness should encourage rather than stifle competition between the services for missions, roles, and capabilities. This concept of jointness aligns with the DoD's Joint Warfighter Concept, which envisions that each service will be able to strike targets deep in enemy territory and defend itself against formidable A2/AD capabilities.[29] The DoD should extend this concept of operations to its concept of procurements by allowing the services to autonomously pursue war-winning innovations. By stimulating competition between the services, the DoD will prepare the Joint Force and the defense industrial base for long-term competition with near-peer and nuclear-armed China and Russia.

Interservice competition will be even more critical in the coming decades as the DoD faces projected downward budgetary pressure. While some assert that a joint framework that follows narrowly defined service roles and mandates a centralized approach to procurements will save the Department money, this approach will have the opposite effect.[30] To make the most limited resources, the

Figure 2. An M109 Paladin gun crew with B Battery, 4th Battalion, 1st Field Artillery Regiment, Division Artillery, at Fort Bliss, Texas, fires into the mountains of Oro Grande Range Complex, New Mexico, on Feb. 14, 2018. (Photo by Spc. Gabrielle Weaver/U.S. Army)[31]

DoD should leverage interservice rivalry to drive cost-saving and performance-enhancing innovation not only on the battlefield, but also in the business operations of running the military, including personnel management, finance and budget, and planning. Competition between the services to remain operationally relevant and aligned to national security will drive improvements in the performance and efficiency of existing military systems and the development of new paradigms that will enable the United States to define the nature of warfare on its own terms.

Military Innovation and Strategic Acquisition at the National Defense University's Dwight D. Eisenhower School for National Security and Resource Strategy

One of the DoD senior service college programs offered at the National Defense University, the Eisenhower School prepares select military officers and civilians for strategic leadership and success in developing national security strategy and in evaluating, marshalling, and managing resources in the execution of that strategy. Formerly called the Industrial College of the Armed Forces (ICAF), the Eisenhower School emphasizes the resource component of national security, with courses on national security studies, strategic leadership, economics, acquisition and innovation, international business environments, and industry. Unique to the Eisenhower School is the Industry Studies program, which consists of courses in industry analysis and an industry studies course, in which students analyze and assess the health of one of 18 separate industry sectors. This program aims to develop the student's strategic perspective on the ability and role of the U.S. and global industrial base in supporting the capability requirements of national security along with the impact of government policy on that industry.[32]

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Army Officer Corps Science, Technology, Engineering and Mathematics (STEM) Foundation Gaps Place Countering Weapons of Mass Destruction (CWMD) Operations at Risk – Part 2*

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Background:

This is the second of three articles from the authors describing the risk to Joint Operations incurred by an Army that is vulnerable to the STEM challenges faced in a great power competition involving CWMD operations. In Part 1, we described the problem: "The Army's failure to emphasize STEM competence in the Army officer corps outside of Functional Areas creates risk to mission accomplishment in CWMD multi-domain operations. The Army must prioritize STEM education in accessions and throughout PME to prepare commanders for effective science and technology (S&T) informed decision making within mission command in CWMD multi-domain operations".[1] For Parts 2 and 3, we utilize the Joint Operational Model, Notional Phasing for Predominant Mili-

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tary Activities, from JP 3-0, Joint Operations², to describe the risk of an Army officer corps lacking STEM dominance for CWMD operations during a regional or great power competition involving CWMD operations. In this article, we address the risk of our current efforts as we operate in Phase 0 (Shape) and Phase 1 (Deter) while our final article (Part 3) will examine the transition to decisive action / unified action with Phase 2 (Seize the Initiative) through Phase 5 (Enable Civil Authority).

Joint / Army Strategy and Doctrine Highlights: Phase 0 (Shape) and Phase 1 (Deter)

Our approach in this article is to first emphasize the applicable tenets from Joint and Army CWMD strategy and doctrine to establish our thesis as relevant and consistent with these documents. We summarize these documents into four themes that describe the operational environment and the importance of human capital in ensuring our preparedness for those challenges. We, then, propose four principles necessary for successful CWMD operations and evaluate the inherent risk in Shape and Deter operations for an Army officer corps that overall lacks core STEM competence.

Shape and Deter operations: the United States Joint Force continuously maintains this posture in every Geographical Combatant Command (GCC) around the world. Unfortunately, daily events in Russia and Ukraine, the Taiwan strait, Korean peninsula, or even in southwest Asia amplify the necessity of our thesis: how soon before the Joint Force is committed to decisive operations in one or more of these areas? The 2018 National Defense Strategy describes the Joint Force in Shape / Deter Operations as the "Global Operating Model". Joint Force capabilities include nuclear; cyber; space; C4ISR; strategic mobility; and counter WMD proliferation as it completes its competition or wartime missions.[3] JP 3-0, Joint Operations, describes Phase 0 (Shape) operations as setting conditions for successful theater operations within a Geographical Combatant Command. "Shaping activities include long-term persistent and preventive military engagement, security cooperation, and deterrence actions to assure friends, build partner capacity and capability, and promote regional stability. They help identify, deter, counter, and/or mitigate competitor and adversary actions that challenge country and regional stability."[4] For Phase 1 (Deter), "Successful deterrence prevents an adversary's undesirable actions, because the adversary perceives an unacceptable risk or cost of acting. Deterrent actions are generally weighted toward protection and security activities that are characterized by preparatory actions to protect friendly forces, assets, and partners, and indicate the intent to execute subsequent phases of the planned operation."[5]

Furthermore, JP 3-40 characterizes the CWMD Activities and Tasks and, though not aligned to the Phasing of JP 3-0, the organizing principles of Prevent and Protect, along with the specialized activities of WMD Pathway Defeat and WMD Defeat, correspond with Shape and Deter Operations.[6] Of note, the "foundational activities and tasks include Maintain and expand technical expertise (recruit, develop, retain)" and the "crosscutting activities and tasks include Understand the environment, threats, and vulnerabilities."[7]

The Army Strategy (2018) assesses the strategic environment to include adversaries leveraging "advanced capabilities such as cyber, counter-space, electronic warfare, robotics, and artificial intelligence." While the U.S. does not seek war with China or Russia, "we are likely to face their systems and methods of warfare as they proliferate military capabilities to others."[8] These include Regional State Adversaries (North Korea and Iran) as well as terrorists and proxies. The Army Modernization Strategy (2021) provides updated vision to the Army Strategy and describes how the Army must modernize to be positioned in 2035 to conduct Multi-Domain Operations by modernizing "how we fight, what we fight with, and who we are."[9] An overarching theme across those domains is S&T dominance. Nested within both strategic documents is the Army Biological Defense Strategy (ABDS). Maintaining the importance of S&T, to correct the "years of atrophy" of our biological defense, the ABDS focuses on four Lines of Effort (LOEs): Knowledge, Biological Defense Situational Awareness, Readiness, and Modernization.[10]

As the Chief of Staff of the Army (CSA) Paper #1 Army Multi-Domain Transformation describes:

In the past, the Army has enjoyed a competitive advantage over any potential adversary in capital, technology, and people. As competitors reduce the technology gap, our people will provide us with an enduring advantage to remain the world's most ready, lethal, and capable land combat force.[11]

The acceleration of innovation and change will increase the technical and cognitive demands on our personnel. This, in turn, will generate new personnel and training requirements. We are transforming how we fight, what we fight with, and how we organize, but we must also transform how we train. The development of our Soldiers' and leaders' technology skills to operate in this significantly more complex environment is at the forefront of the Army's strategy.[12]

Finally, ADP 6-0 defines Mission Command and specifically articulates a commander's decision-making process: "Commanders make decisions using judgement acquired from experience, training, and study." Furthermore, foundational to leadership is a commander's understanding:

An operational environment encompasses physical areas of the air, land, maritime, space, and cyberspace domains as well as the information environment, the electromagnetic spectrum, and other factors. Understanding an operational environment and associated problems is fundamental to establishing a situation's context and visualizing operations. The interrelationship of the air, land, maritime, space, and cyberspace domains and the information environment requires a cross-domain understanding of an operational environment. While understanding the land domain is essential, commanders consider the influence of other domains and the information environment on land operations. They also consider how land power can influence operations in the other domains. For example, commanders consider how friendly and enemy air and missile defense capabilities influence operations in the air domain. Included within these areas are the enemy, friendly, and neutral actors who are relevant to a specific operation.[14]

ADP 6-0 elaborates on commanders making decisions in time: "Timely decisions and actions are essential for effective command and control. Commanders who demonstrate the agility to consistently make appropriate decisions faster than their opponents have a significant advantage. By the time the slower commander decides and acts, the faster one has already changed the situation, rendering the slower commander's actions irrelevant. With such an advantage, the faster commander can dictate the tempo and maintain the operational initiative."[15]

Finally, within control, commanders and staff utilize the "operational variables (political, military, economic, social, information, infrastructure, physical environment, and time—known as PMESII-PT) and mission variables (mission, enemy, terrain and weather, troops, and support available, time available and civil considerations—known as METT-TC)" to analyze and describe the operational environment.[16]

From these highlighted doctrinal and strategy passages, we derive the following four themes: 1) Shape and Deter CWMD operations are ongoing in every GCC to varying degrees; 2) Great power competition and regional state adversaries possess significant WMD capabilities / facilities; any movement beyond Deter will result in multi-domain operations where Joint Forces will conduct CWMD tasks / activities and likely CBRN response; 3) Human talent is the Army's priority capability and S&T skills will provide the advantage in CWMD operations; 4) Commanders make correct, timely decisions based upon understanding, intuition, staff recommendations, and critical analysis. Shape, Deter, and ultimately wars are won based upon the decisions of commanders. In summary, CWMD multi-domain operations present the convergence of complexity in command, control, risk to force, risk to civilian populations, risk to political / national will, and S&T informed decision making. Whether responding to the aggression of a near peer or regional state adversary, the Army officer (commander and staffs) as a component of the Joint Force must understand the capabilities and advancements that these aggressors pose in real-time, as our adversaries' ability to employ emerging technologies affects every phase of joint operations. The understanding of these emerging technologies by only specialized Army officers makes these threats ever more lethal as units of every echelon become more susceptible in linear or non-linear operations to their effects. As the Army recalibrates the skills required from a counterinsurgency concentration to great-power / near-peer competition, STEM competence in the officer corps is essential.

CWMD Phase 0 and Phase 1 Activities:
As outlined above, Joint and Army doctrine provides vision, direction, tasks, and activities for Phase 0 and Phase 1 operations. With respect to CWMD operations, Shape and Deter has largely characterized Joint conventional CWMD operations since possibly 2003 with the Iraq invasion and hunt for WMD. Phase 2 and beyond CWMD operations in a regional or near-peer competition have not occurred; our evaluation is based upon our experience observing Shape and Deter operations over the past 10-30 years in multiple GCCs. Accordingly, we constructed four organizational principles to guide our CWMD risk evaluation as it relates specifically to our thesis: CWMD deficiency in the Army officer corps presents great risk to successful conduct of CWMD operations in regional or great power competition. Our organizing principles to evaluate CWMD risk are as follows: 1) STEM Undergraduate / Graduate Education, Leader development, and Professional Military Education (PME); 2) Threat modeling and WMD Pathway defeat; 3) Doctrine / Training / WMD defeat; and 4) Acquisition / Science/ Technology development. To substantiate the premise of our argument, we will emphasize how our principles though postulated discreetly from the Army Modernization Strategy and ABDS four lines of effort are congruent with both Army Strategy documents.

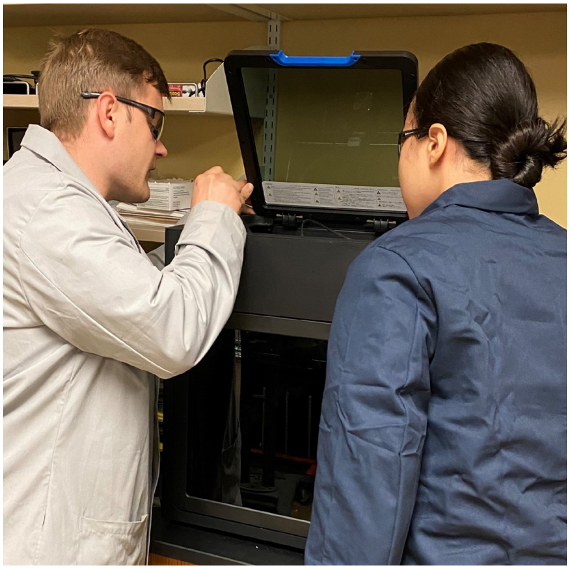

Figure 1. MAJ Patrick Bowers and CDT Valencia Ramirez observe a 3D printer during operation. The print was utilized in MAJ Bowers' soft robotics research

STEM Undergraduate / Graduate Education, Leader development, and Professional Military Education:

Every foreseeable theater of operations for the Joint Force for the next 20 years will involve integrating novel S&T applications to provide advantages and solutions to overcome CWMD challenges in decisive operations. STEM competence will be a necessity in Phase 2 (Seize the Initiative) CWMD operations; however, the competence gained through advanced degree programs is largely confined to functional areas and officers selected to teach at the United States Military Academy. STEM-competence cannot be achieved rapidly. A Masters in a STEM-discipline requires two years and considerable research; the PhD requires an additional three or more years of laboratory, design or computations research. This is not a 3 or 6-month ramp up to gain depth and breadth and the complex-problem solving required for multi-domain CWMD operations. This requires professional development in the same manner as the aviation officer, maneuver, or sustainment officer spends years gaining competence in those fields. Further, STEM competence builds on undergraduate STEM foundations that are not widely present in the Army officer corps.[17] We elevate "operational experience" in the officer corps through development experience and relegate advanced STEM-education to those who will not command. Are combined arms operations at the battalion, brigade, and division so fundamentally different that an officer must devote 20+ years within those organizations to gain and demonstrate competence? Can the talented commander not spend 75% of that time in those organizations and 25% gaining the STEM competence to truly be a forward-thinking tactical and operational leader? As the ADP 6-0 excerpts illustrated earlier, a commander's understanding and decision making is a direct result of his / her education and experience. The Army cannot expect its operational commanders to make the most STEM-informed decision when the Army has not continuously developed the leader in that capacity. Exclusive reliance on staff officers for STEM analysis and recommendations, places command decisions at risk of lacking the lens to critically evaluate information and decision space. Additionally, for tactical level / company grade commanders to possess STEM-disciplines they must obtain those through their commissioning sources. As discussed during Part 1, a minority of commissioned officers possess a bachelors in a STEM-discipline and this percentage decreases based upon years of active federal service. Further, undergraduate STEM foundations, if not reinforced and expanded through graduate education, obsolesce, and degrade over time.

The strategic environment requires the Army to "maintain established subject matter expertise while cultivating much-needed NEW expertise within the Force". This assessment underscores the need for officers with advanced technical degrees who will also play a vital role in engaging our allies and partners. Such officers meet the need for "agility in biological defense," and by extension CWMD operations, through creativity and innovative thinking.[18] Clearly, the Army has a need for more officers with science backgrounds who can reason quickly during compressed reaction times and shortened decision cycles.

The reality for many company and field grade officers in basic branches is they may experience risk of promotion and certainly command when they accept an advanced civil schooling opportunity. More senior officers may discourage this path because they perceive it will likely harm the junior officer's career. Senior officers often instead advocate one-year PME (CGSC / AWC) and masters-level education in non-STEM fields. Currently there is no focus related specifically to STEM concepts included in any level of formalized PME, including Basic Officer Leader Course, the Captain's Career Course, the Command and General Staff College, or the Army War College. Throughout these courses officers may be exposed to some applications or planning considerations for CWMD operations or emerging S&T capabilities, but there is limited formalized education regarding the STEM background of these situations. This presents a situation where officers are making decisions with minimal knowledge on how to mitigate the effects of a CBRN scenario.

As a whole, the Army PME aligns with non-STEM advanced degree (humanities-based education) opportunities which lack scientific and technical rigor. Advanced STEM degrees can only be obtained through other opportunities, often at technical institutions of the other services: Naval Post-graduate School (NPS) and Air Force Institute of Technology (AFIT). Both institutions routinely provide their officers with scientific and engineering graduate education. A comparable institution for the Army does not exist.

The Army Modernization Strategy recommends "to update its leader development and education processes to increase critical, creative, and systems thinking so that the next generations of Army leaders and warfighters are prepared for the complexities of MDO."[19] STEM education is a central component of critical, creative, and systems thinking.

ABDS promotes Knowledge as the first necessary LOE because "without a strong basis in scientific knowledge and understanding, biological defense situational awareness and readiness are not possible, and the modernization needed to defend against new but uncertain…threats and hazards cannot be attained." However, biological defense knowledge in the Army has deteriorated. Consequently, new development of talent management is required. ABDS depends on "scientific and medical expertise". The strategy takes this a step further by advocating that "knowledge must be embedded in professional military education at all levels… [in order to] enable knowledge-based decision making."[20]

In summary, because we postulate a STEM-trained commander (bachelors / advanced degree) will make a better decision when faced with a S&T challenge in multi-domain CWMD operations, then the Army is assuming great risk in not prioritizing officer STEM education and expertise. During Phase 2-3 CWMD operations if this postulate is validated, it will be too late to correct this deficiency due to duration and intensity of obtaining an advanced STEM degree.

Threat modeling and WMD Pathway defeat:

Who are the officers with tactical experience developing the computer, AI, and technical models to describe the CWMD threat? Such officers must understand the capabilities and limitations of nuclear and chemical weapons, pathogens, virus infectivity, detectors, sensors, environmental hazards, civilian population movements, and assumed parameters which feed the sophisticated models. Without STEM education, CWMD operational models simply exist as a "black box" for most Army officers.

Who are the technical experts in the Army contributing to WMD Pathway defeat? Is this a technical skill possessed and coveted by maneuver, fires, and effects officers or is this important skill set compartmented to civilians, other services, Special Forces, and Operations Support officers? To contribute and develop innovative, effective solutions in WMD Pathway defeat, STEM-competence is a necessity. S&T critical thinking and understanding is paramount to WMD Pathway defeat.

Along these lines, the COVID-19 pandemic demonstrated to the world the power of a biological pathogen, expert opinions, medical treatment capacity / vulnerability, social media information dissemination and control, and the difference in decision-making by government authorities when presented with the same general facts. The Joint Force will undoubtedly rely heavily on the initial assessment and recommendations of leaders at the point of contact, and these leaders must understand STEM capabilities and concepts to depict an accurate understanding of the operational environment for supporting agencies to effectively assess the situation. What is the depth of CWMD expertise in any Army unit? In an Army Brigade Combat Team, the CWMD experts are the CBRN officer (with four to six years in the Army) and the brigade surgeon (a physician with probably limited knowledge on biological weapons transmission). Certainly, there are supporting headquarters and other agencies that can contribute to knowledge in these situations; however, the "expert" opinion in that organization often holds the greatest sway. A STEM-competent force provides depth and critical thinking to ensure the most appropriate staff recommendations and command decisions. Conventional forces need to be able to react to the full spectrum of WMD threats, and it cannot rely solely on the STEM expertise of supporting agencies, as they could be limited in their ability to rapidly respond to the force's immediate threats.

The Army Modernization Strategy describes this as "How We Fight". "The MDO capable force will combine tailorable formations of networked manned and unmanned platforms, fires, electronic warfare, cyber, intelligence, surveillance, reconnaissance, engineers, sustainment, communications, and protection capabilities at all echelons, from squad to theater."[21] And furthermore, "An MDO capable force will allow the Army, a part of an integrated Joint Force, to expand the options available to civilian authorities, to include effective deterrence and competition short of armed conflict, or timely response to an attack attempting to permanently change the status quo."[22] Integrating S&T across multi-domain operations into Shape and Deter CWMD requires commanders and staff competent and confident in STEM.

The second line of effort of ABDS is Biological Defense Situational Awareness to support decision-making. Army officers with STEM backgrounds are better able to "identify and analyze how the adversary may exploit biological threats and hazards in novel ways and recommend countermeasures."[23] Consider the possible threat posed by drone swarms and CBRN weapons. Such swarms are of great interest to our adversaries because they offer a dynamic capability to complement, challenge, and substitute. Swarms may enhance delivery of CBRN weapons, serve deterrent/detector roles, or simply achieve similar effects of CBRN weapons. Furthermore, non-state actors, such as ISIS have demonstrated their capacity to employ drones with devastating effects as well as their willingness to kill civilians via chemical attacks.[24]

The ABDS strategy justifiably assumes the biological attacks are neither deterred nor prevented by CWMD efforts alone. In many cases, early detection of biological attacks remains elusive due to long incubation periods and high transmissibility. The stealth-like nature of such bioweapons offers anonymity to our adversaries, who can evade attribution. Consequently, the use of deadly toxins and pathogens proves to be an attractive option for our enemies.[25]

In summary, constraining STEM and WMD expertise to particular branches and functional areas, holds risk in CWMD Shape and Deter operations. The Army officer corps gains strength through depth; CWMD is a whole of Service problem set. If only "experts" understand the S&T of CWMD operations and WMD effects, then commanders are dependent upon experts who as evidenced by this pandemic can differ widely in their advice and recommendations. Commanders must possess the CWMD situational awareness to be able to make right decisions.

Doctrine / Training / WMD defeat:

Army / Joint CWMD doctrine is conservative, conventional, and not predictive. To be predictive, doctrine writers must be able to envision how future technologies can be integrated into CWMD operations. Are the officers developing and writing CWMD doctrine reading and writing in current nuclear, chemical and biotechnology fields or are they trained through Army schools and operational experience? Innovation does not normally arise through new applications of approved ideas but through new ideas and new technologies. Applying new technologies requires a STEM-educated officer with continued STEM Professional Military Education (PME).

In one theater of operations, the Army is appropriately focused on CWMD operations: Korea. For example, the 2nd Infantry Division must remain prepared for possible CWMD operations on the Korean peninsula. Working closely together, US and ROK partners train for CWMD tactical operations.[26] Technical enablers such as the CBRN response teams and nuclear disablement teams from the 20th CBRNE Command provide valuable support.[27] Korea conducts multiple theater-level computer exercises, CWMD focused combined training exercises, Noncombatant Evacuation Operations (NEO) and many other training scenarios that incorporate CWMD into the main training threads. As discussed repeatedly, this scenario is not unique to Korea but is almost ubiquitous in any likely location for Army forces to be committed. The high-level of training serves the JP 3-40 WMD defeat task and activity. A trained and ready force is a significant deterrent to WMD employment because the adversary cannot assume the WMD will have the desired effect.

The Army Modernization Strategy identifies the Synthetic Training Environment (STE) in relation to Army Futures Command Cross Functional Teams (CFT) ensuring new requirements are being matched to capabilities.[28] CWMD operations must be integrated into this new training paradigm. STEM and CWMD competence in the Army officers building the STE is critical to ensuring realistic and anticipatory training is a component of future unit training plans.

Doctrine / Training and WMD Defeat directly support the third LOE of ABDS (Readiness), which hinges on subject matter expertise. Strengthening our biological defense requires "…commanders and staff at all levels have access to the biological subject matter expertise needed to support situational awareness and response decision making."[29] Army officers who have earned formal degrees in STEM are aptly suited to meet this need. Their education enables these officers to communicate and collaborate across DoD agencies as well as allies and partners.

Acquisition / Science/ Technology Development:

This is the most important area of emphasis for CWMD Shape operations. The Acquisition Corps and all Army Futures Command leaders must be STEM-educated and have advanced STEM degrees in their areas of expertise / responsibility. Acquisition and development are just not leadership, processes, and procurement regulations: it addresses the fundamental question of whether this weapons system or technology is applicable to today's available technology or tomorrow's required capability. S&T engineering questions embraced by Army officers with years of operational experience combined with advanced engineering degrees, and best business practices will significantly improve Army acquisition success. The result is a modernized fighting force, which supports the Army modernization priorities.

The risk to Shape and Deter operations is especially difficult to measure or quantify within this principle. How would the development and delivery of new CWMD technologies be different if STEM-educated, tactically competent officers were deeply-invested in the acquisition process? We believe the CWMD system would be more likely to meet the anticipated need and durability of the requirement due to the sustained involvement of the officer, and when the system is fielded, the Army officer would better understand its capabilities and limitations for employment based upon his / her S&T contribution to its development. This requires a fundamental shift in how the Army values officer experiences: Cross-Functional Teams should be a highly regarded and competitive assignment for advanced degree STEM-trained field grade officers. If the Army expects to achieve its Modernization Strategy, then officer assignments to CFTs with the requisite technical competence should be a key development assignment.

The Army Modernization Strategy devotes the largest portion to this concept, "What we fight with." The six modernization priorities and 31 CFT efforts will be achieved through advanced S&T development and integration into the force.[30] STEM-competent officers are required for implementation of this effort. There is great risk we cannot achieve these objectives by 2035 without forwarding-thinking STEM-trained leaders to guide these programs.

The fourth LOE of the ABDS (Modernization) explicitly calls for "…the requisite manning (skill, rank, and distribution) of biological defense expertise…". Integration of "subject matter expertise into operational decision-making and response" is emphasized along with the modernization of equipment and facilities.[31]

Our Recommendations:

In this conclusion of Part 2, we propose our solutions to this identified risk. In Part 3, we will elaborate on our recommendations and provide actionable and measurable strategies and outcomes for fundamentally changing the Army's approach to STEM education and CWMD operations. In the meantime….

1. STEM degrees required in >50% of all ROTC scholarship awardees / service academy graduates.
2. Advanced STEM degree opportunities for company / field grade (MS) and senior field grade officers (PhD); successful completion of the degree achieving a required GPA / research completion (thesis / dissertation) will be viewed as equivalent to the commensurate above center of mass (ACOM) Officer Evaluation Reports for promotion board selection. The current Additional Service Obligation (ADSO) requirements remain for ACS-funded education.
3. Professional scholarship in the officer corps should be expected. New ideas will be generated with the free exchange of ideas, especially when officers are rewarded and selected for how they think, not just their results.
4. Army acquisition, Futures Command, and doctrine developers must be STEM-competent in the disciplines appropriate for their responsibilities.
5. CWMD operations should be included as a planning and operational objective during every training center rotation and into the STE. We have established that every theater of operations expects to encounter CBRN effects or conduct CWMD operations during Phase 2-5 Joint Force operations. This should be our routine and not restricted to a Korean peninsula training scenario.
6. Conduct a funded internal and external review to determine the applicability of adding a Master of Science degree capacity in STEM disciplines to the United States Military Academy (commensurate with AFIT or NPS) with partnered research throughout Army Futures Command in order to expand PME opportunities and develop STEM competent field-grade officers.

Figure 2. Cadet (now second lieutenant) Kirsten O'Keefe briefs Brigadier General Shane Reeves, the Dean of the Academic Board of the United States Military Academy at West Point, on her group's research poster, at West Point Projects Day 2022 (photo taken by Major William Horne, April 28, 2022).

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Operational Survivability on the Modern WMD Battlefield

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Headquarters, Department of the Army, G-3/5/7

Abstract

Preservation of personnel and materiel combat power in tactical and operational nuclear environments is essential for enemy overmatch and mission success. Survivable Soldiers and materiel in maneuver and support formations are the fundamental lynchpin of the Army's credible deterrent in dominating weapons of mass destruction (WMD) environments. Operational survivability is the ability of personnel and materiel to survive in and through nuclear environments while solidifying the convergence of the human-materiel interface informing commanders of combat power availability, reliability, and operability. Computational models of WMD effects on Army formations provide commanders with a near real-time assessment to inform tactics, techniques, and procedures during training and exercises in preparation for the modern battlefield.

Background

The Army operates across all domains along a distributed geographic scale. While the physical distance is daunting the battlefield remains congested, potentially contaminated, with a wide variety of adversarial capabilities to include cyber, space, electronic warfare, robotics and artificial intelligence. Sophisticated Great Power competitors deploy and employ weapons of mass destruction (WMD) to thwart our Nation's interests, directly and indirectly, at a scale capable of impeding Army objectives.[1]

A WMD survivable infrastructure of crew-served and autonomous systems underscores Army plans and strategic objectives. The infrastructure ensures necessary combat capability for follow-on engagements and decisive actions. Survivable materiel provides the ground commander with a lethal overmatch against the adversary forces regardless of the battle phase. Materiel design, manufacture, development, and fielding conducted in a deliberate manner accounts for threat-informed usage in operational environments and reduces the fiscal impact. Risk-informed need-based investments account for the end-user requirements while driving the design and development of CBRN survivability criteria tailored to overwhelm adversarial threats.

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Since Great Power competitors have openly advertised a strategy of limited nuclear use, the Army must be prepared to fight, survive, and win in a conventional nuclear integrated environment. Limited nuclear use will disrupt the ability of friendly forces to maneuver across the battlefield. However, maneuver disruption becomes even greater when formations are neither survivable against the threats nor knowledgeable of the threat impacts. As designed, WMD employment inflicts grave infrastructural, psychological, and economic damage to achieve physical and non-physical objectives consistent with strategic ends. The Army must prepare for the use of WMDs on both the forward edge of the battle area and the strategic support areas providing readiness safe havens and combat generation platforms. Prior preparations provide a bulwark against enemy WMD activities attempting to deny friendly actions required for effective deterrence.

Survivability

The Army's credible deterrence directly correlates to formations' survivability and operability on the WMD battlefield. Survivable multi-domain formations enable the Army to stimulate, see, and strike key components and vulnerabilities within enemy territory. Survivability is not a new concept. In fact, Joint Publications (JP) 1-02 and 3-34 define survivability as all aspects of protecting personnel, weapons, and supplies while simultaneously deceiving the enemy.[2] Related to the survivability concept and inherent within the commander's decision calculus are the key terms of reliability, confidence, availability, and operability (all of which are not specifically defined in JP 1-02). Reliability is the probability of performing an assigned purpose for a specified period under the operation condition encountered.[3] Similarly, the term confidence extends this concept by establishing a degree of trust and belief in the reliability of a person or thing. A commander depends on operability and quantity of personnel, weapon systems, and availability of supplies at specific times. In this manner, a commander assesses the operability of unit materiel and personnel with a degree of confidence driven by understanding degradation with respect to conventional and WMD effects across time, distance, and employment specifics. Acknowledging that no unit, at any echelon, fights with 100% availability and operability, commanders accept a measure of risk, either to mission or to force. Risk directly relates to tolerance and spans the gap between specifications/requirements and reality.

Protection Concept

Future battlefields will contest international norms and known expectations to achieve strategic objectives. The contestation introduces challenges across a host of threats and requires commanders to not only accept risk but also be innovative in incorporating their formation's capabilities to achieve the objectives and complete the mission. Joint Publication 3-0 identifies seven common functions enabling commanders to integrate, synchronize, and direct operations.[4] A vital function is protection. Protection seeks to preserve critical capabilities, assets, and activities (CCAA), denying threat and enemy freedom of action, and enables access.[5]

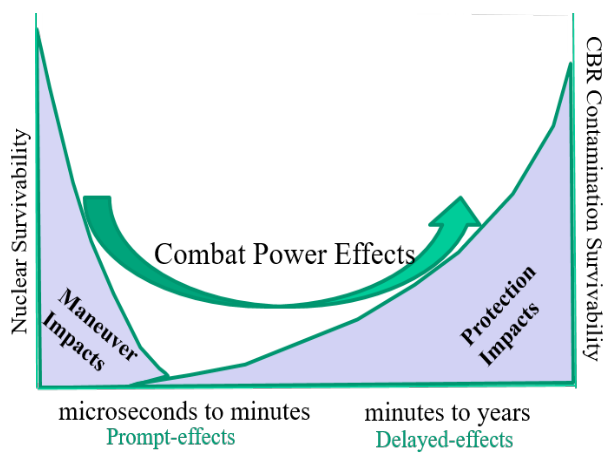

Figure 1. Survivability effects on combat power.

Protection requires active involvement from the commander to survive and win in large-scale combat across the multi-domain operational environment. WMD use, specifically nuclear, challenges large-scale combat across time and a geographically distributed space creating two operational environments. The initial nuclear effects on formations and infrastructure across time and distance from nuclear employment, directly affect combat effectiveness and combat power within the following delayed contamination environment (Figure 1).

WMD (Nuclear) Threats

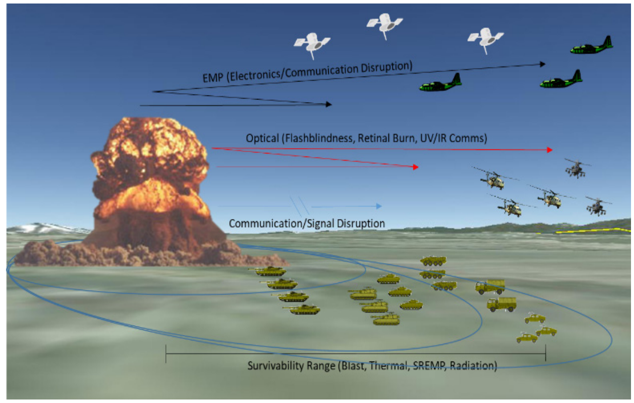

Figure 2. Visual description of nuclear phenomenology effects.

Combatant commanders have the responsibility for ensuring that their theater objectives and requirements are threat-informed enabling force provider formations to account for the nuclear effects spectrum within their battle space (Figure 2). Due to the physics-based nature of nuclear phenomenology (energy emission across the electromagnetic spectrum through the atmosphere), computational modeling aligns very well with assessing initial nuclear weapon effects on formations. Threat-, materiel-, and personnel-integrated modeling and simulation environments enable commanders to assess formation capabilities and tactics in a nuclear environment by incorporating system survivability metadata within a system-of-systems approach for a variety of postures including offensive and defensive. System-of-systems models integrated into existing training and exercise simulation platforms support assessment of operational plans and strategies. Realistic development and operational test scenarios, based on validated initial and delayed nuclear environments, support the commander in defining potential risks-to-mission.

Operational Survivability

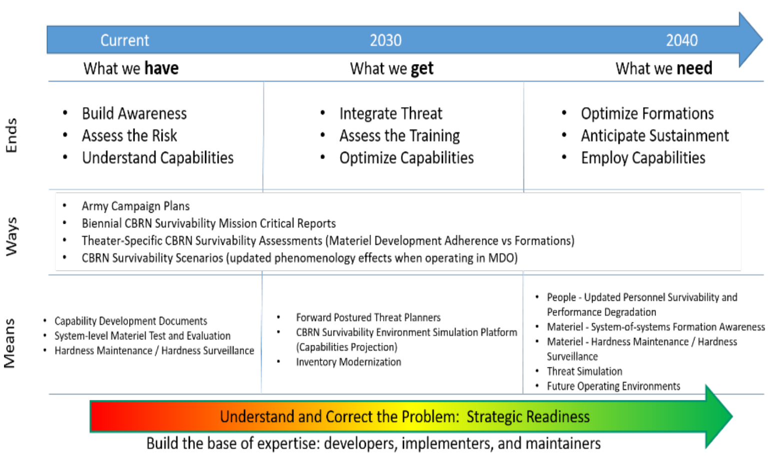

Figure 3. Ends, Ways, and Means to address strategic readiness in WMD environments.

Underscoring Army plans and strategic readiness against near-peer adversaries are basic requirements for survivable materiel/infrastructures, both crew-served and autonomous, capable of operating in and through nuclear environments while maintaining combat power for follow-on engagements and decisive actions (Figure 3). Operational survivability describes the convergence of materiel and personnel survivability while providing the commander a conceptual basis to estimating combat power availability and operability. In a nuclear environment, personnel and electronics are much more vulnerable than the military vehicle system. Emphasizing reconstitution of cross-trained personnel and knowing associated health effects within the different crew-served compartments is critical.

The Army must assess combat power degradation in a modern nuclear environment to decrease the risk-to-mission. Updated threat-informed studies provide the necessary basis to quantify current battlefield formation combat power estimates. The studies validate current assumptions and address survivability impacts related to degraded operations. Army test, evaluation, and assessment capabilities do not completely address maneuver formation operational nuclear survivability. Modernization of survivability regulations, processes, and assessment tools mitigate the risk of systems and formations becoming combat ineffective following a nuclear detonation. Deliberate modernization in this manner provides the Army an ability to near-real time assess materiel and personnel survivability. Non-computational training environments do not realistically simulate the breadth and scope of combined nuclear weapon effects on Army maneuver units. Therefore, the commander is at a loss due to inadequate information contributing to an inability in developing mitigation strategies enabling operational success. Available materiel test and evaluation metadata combined with known radiation, blast, and thermal health effects provide a sufficient mechanism to quantitatively estimate and contribute to the operational survivability assessment. Computational codes account for varying nuclear weapon effects on materiel and personnel. Simulation platforms play a crucial role in life-cycle management by enabling end user understanding of nuclear weapon effects variability with respect to materiel modifications and alternatives.

Conclusion

"*Future adversaries will leverage components of space, cyberspace, electromagnetic warfare and information to challenge friendly freedom of action.*" [6]

Success on the modern WMD battlefield is dependent on capability and materiel developers ensuring current and future mission critical electronic and crew-served weapon systems are survivable in the multi-domain environment. The Army must assess the survivability of formations at echelon while operating in WMD environments by initiating broad scope modeling and simulation efforts from a system-of-systems survivability perspective. Updated operational survivability information enables multiple Army communities including the Force Health Protection community to develop strategies for increasing return-to-duty rates contributing to combat power sustainment. The Army increases the credible deterrent dominance by characterizing, analyzing, and demonstrating operational readiness in a nuclear and CBR-contaminated environment.

Notes

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The Unknown Unknowns of Paleovirus Hunting

LTC Dana Perkins, PhD

U.S. Army War College

Introduction

After a 3,000 year-long run as the greatest scourge to humankind, the last known case of naturally acquired smallpox occurred in Somalia in 1977 with the World Health Assembly in 1980 declaring the disease eradicated. In between these events, history recorded the case of Janet Parker, a photographer at the Birmingham University Medical School, who got infected and died of smallpox as a result of the virus escaping a research laboratory.[1] Smallpox still maintains the distinction of being the only eradicated human infectious disease matched only by the rinderpest as the only animal disease eradicated in 2011 with the last identified case dating back to 2001 in Kenya.

The eradication of the smallpox and rinderpest diseases are considered the most remarkable achievements in the history of humankind in terms of international collaboration and commitment and strong leadership from intergovernmental organizations such as the World Health Organization (WHO), the Organization for Animal Health, and the Food and Agricultural Organization. However, neither of these achievements would have been possible without the scientific breakthroughs over the past two centuries that led to the discovery of effective vaccines and adequate prevention and control measures.

Similarly demonstrated by the current COVID-19 pandemic, scientific research is essential to developing medical countermeasures to mitigate the risks of infectious diseases. As our global laboratory capabilities expanded to accommodate the research on dangerous pathogens, the need for effective biorisk management frameworks and systems to mitigate the potential of accidental or deliberate release of biological agents from the laboratories has become ever more critical for protecting the health and safety of laboratory workers and for preventing laboratory-originated community outbreaks or even pandemics. While an international database of laboratory incidents and near-misses does not yet exist and the first laboratory-acquired infection (LAI) was reported back in 1897,[2] recent research from Asia-Pacific region shows, for example, that LAIs occur primarily in research laboratories and across the spectrum of national income, from low-middle LMIC) to upper-middle (UMIC) and high income (HIC) countries. Many of these laboratories in LMIC or UMIC, whether involved in research or other public health activities such as disease surveillance or clinical diagnosis, lack an effective national biosafety[3] and biosecurity framework.[4] Terrorists, extremists, and disgruntled employees may also see these laboratories as potential sources of biological agents that may illegitimately acquire to inflict harm on their targets and advance their agenda. Yet,

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globally, even though the United Nations Global Counter-Terrorism Strategy called on its Office for Disarmament Affairs to develop a database of biological incidents,[5] no such comprehensive database currently exists.

Even in the United States, biological incidents have been under intense scrutiny since 2014 when federal agencies reported mishandling of dangerous pathogens in several incidents that raised biosafety and biosecurity concerns[6]. These incidents also prompted an unprecedented effort to optimize biosafety and biosecurity[7,8,9,] including publishing annual reports on the operational metrics of the Federal Select Agent Program.[10]

The Global Health Security Index (GHSI),[11] published in December 2021, assessed the health security capabilities of 195 countries and concluded that 91% of countries lack effective biosecurity capabilities addressing whole-of-government biosecurity systems, biosecurity training and practices, personnel vetting and controlled access to sensitive locations, secure and safe transport of infectious substances, and cross-border transfer and screening biosecurity. Moreover, the 2021 GHSI also shows that 94% of countries have no national-level oversight measures for dual-use research, which includes national laws or regulation on oversight, an agency responsible for the oversight, or evidence of a national assessment of dual-use research. This general lack of preparedness to mitigate current and future threats is compounded by the challenges posed by advances in biotechnology and the lack of viable options to regulate the gene synthesis industry[12] to ensure that the potential misuse of synthetic biology is minimized. Therefore, the public's distrust of science,[13] the SARS CoV-2 "lab-leak theory" gaining ground,[14] and the calls for increased transparency and accountability in reporting LAIs[15] should not surprise anyone.

The two officially designated repositories of variola virus in the world, the Centers for Disease Control and Prevention (CDC) in Atlanta, GA, and the State Research Centre for Virology and. Biotechnology (VECTOR) in Koltsovo, Russia, were not free of controversy. Just a few years ago, seventy-five CDC laboratorians were potentially exposed to anthrax due to improperly following inactivation procedures.[16] Apart from already having a reputation to contend with, as a research institute part of the Biopreparat, the former Soviet Union's biological weapons production enterprise, VECTOR had its share of laboratory incidents, including the death of a female scientist in 2004 from an accidental Ebola virus needle stick[17] and an explosion in September 2019 still shrouded in mystery even though VECTOR reassured WHO that the smallpox repository was not affected.[18] While the smallpox repositories may be secured, at least according to WHO reports of its periodic visits to assess biosafety and biosecurity at these centers,[19] the lack of transparency with regard to other research activities at VECTOR and political statements from the Putin Administration about developing "genetic weapons"[20] are disconcerting to say the least.

VECTOR announced recently that it will be conducting research on paleoviruses to understand virus evolution by analyzing the remains of animals (such as mammoths and other prehistoric animal carcasses recovered from melted permafrost)[21] and that research is under way[22]. While there may be relevant questions to be asked about ancient viruses and "evolutionary arms races"[23,24] one cannot help but wonder whether any extinct paleoviruses, if isolated and reconstructed (similar to the 1918 Influenza virus),[25] may escape the laboratory and be re-introduced into the human population or into a suitable animal reservoir. As of now, only a novel virus that can infect amoebas has been successfully revived by a French team . The interest in reviving ancient viruses is not new. In 1951, a graduate student named John Hultin dug up bodies of Spanish flu victims in Alaska and attempted to isolate (unsuccessfully) the virus from their lung tissues[27] and, in 1991, VECTOR scientists were able to extract viral DNA but not live virus from the scabs of smallpox victims buried in the permafrost but brought up to the surface due to flooding.[28] A video of the 1991 Kolyma expedition, courtesy of the late Vector scientist, Dr. Evgeny Belanov, shows the variola samples' trek from corpses in Kolyma to the Vector biosafety level 4 laboratories at Vector for virus isolation, electron microscopy, and molecular biology studies (select screenshots shown in Figures 1-4).

Figure 1: Screenshot of an image from the video of the 1991 Kolyma expedition showing a corpse unearthed by Vector scientists

Figure 2: Screenshot of an image from the video of the 1991 Kolyma expedition showing Vector scientists decontaminating themselves and their equipment in the field

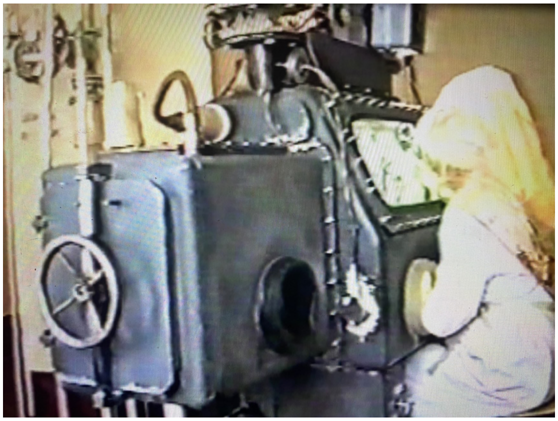

Figure 3: Screenshot of an image from the video of the 1991 Kolyma expedition showing the processing of variola sample in a glove box at Vector (outside view)

Figure 4: Screenshot of an image from the video of the 1991 Kolyma expedition showing the processing of variola sample in a glove box at Vector (inside view)

Since then, technology has advanced by leaps and bounds as shown by the reconstruction of the 1918 flu virus by CDC in 2004 and, on smallpox, the conclusion of the deliberations of the WHO Scientific Working Group convened in 2015 that:

"With the rapid advances in synthetic biology, there is now the capability to recreate the variola virus, the causative agent of smallpox. While recreating variola is quite complex, it is increasingly possible due to the availability of genetic material and of machines for complex assembly, as well as increasing know-how among a broad array of persons. Furthermore, the rapid rise in availability of genetic material from commercial sources and the so-called "grey market" is driving the cost of this material down, making recreation possible by multiple institutions and persons, including those with malicious intent. The "WHO Recommendations concerning the distribution, handling and synthesis of variola virus DNA" should be revised. Consideration should be given to adding a component or separate document on guidance to commercial DNA providers for screening requests for DNA fragments. With the development of these technologies, public health agencies have to be aware that henceforth there will always be the potential to recreate variola virus, and therefore the risk of smallpox re-emerging can never be fully eradicated".[29]

The International Federation of the Red Cross and Red Crescent Societies called climate change" an even more significant threat to humanity than the COVID-19 pandemic".[30] That is particularly true for indigenous peoples of the Arctic (about one million people across eight countries) that may suffer from an increased future burden of vector-, air-, food,- and water-borne diseases and zoonoses as a consequence of climate change[31] while already having had, historically, according to the Arctic Council, "a higher pandemic mortality rate" whether that was due to smallpox, Spanish flu, measles, or other infectious diseases due to geographic isolation, low immunity, underlying chronic conditions, or lack of critical healthcare infrastructure among other factors.[32]

Our global scientific capabilities to quickly develop medical countermeasures against SARS-CoV-2 virus to tackle the current pandemic were due in part to the fact that coronaviruses were known pathogens with the first virus of this family being discovered in 1937[33] and that significant human and financial resources were targeted toward this outcome. Even so, the COVID-19 pandemic exposed vulnerabilities in public health systems and supply chains worldwide that were difficult to predict just short of two years ago. The unknown unknowns lurking in the permafrost melting due to global warming or exposed due to industrial exploitation may be the cause of a future outbreak or pandemic that will reveal even deeper vulnerabilities in our global preparedness. We must ensure responsible conduct in the life sciences and effective best practices in biosafety and biosecurity while mitigating the risks of synthetic biology in order to avoid a potential paleovirus pandemic with laboratory origin.

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Aerial Radiation Detection Identification and Measurement System Detector Material Comparison Study

CPT Benjamin C. Troxell, CPT Kacey D. McGee and LTC Christina L. Dugan PhD

20th Chemical Biological Radiological Nuclear and Explosives Command (CBRNE)

Abstract

The 20th Chemical Biological Radiological Nuclear and Explosives Command (CBRNE) currently utilizes an airborne sodium iodide gamma and beta detection system to map radiation fields over large areas of interest. The 20th CBRNE explored emergent detector technologies utilizing two detection materials; thallium-activated cesium iodide and high purity germanium (HPGe). These detectors were simulated at various altitudes and compared to background measurements. The sodium iodide detector failed to provide isotopic discrimination at distance. The thallium-activated cesium iodide CsI(Tl) detector provided sufficient absolute efficiency and energy resolution to identify isotopics at distance. The HPGe detector provided the best energy resolution. However, current crystal growth technology limits the size of HPGe detectors. New CsI(Tl) detectors would enable source identification by the Aerial Radiation Detection Identification and Measurement System (ARDIMS).

Index Terms — *thallium-activated cesium iodide CsI(Tl) material, high purity germanium HPGe, gaussian energy broadening constants, GEB, gamma spectrum, MCNP*

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I. Introduction

Aerial radiation detection is challenged by the extreme distance between a radiation source and detector. This challenge is only amplified when applied to wide area survey. The 20th CBRNE currently utilizes the Aerial Radiation Detection Identification and Measurement System (ARDIMS) to conduct area survey. The ARDIMS utilizes thallium-doped sodium iodide NaI(Tl) detectors to identify wide-area gamma contamination and lithium-loaded glass fiber neutron detectors to detect the presence of neutron sources.[1] In a typical flight configuration, the ARDIMS is equipped with three gamma detection pods and one neutron detection pod. The three gamma detection pods each consist of four 16x4x2 in NaI(Tl) detectors. The single neutron detection pod consists of two Li6 glass scintillator detectors.[1] The system is manned by one operator. The operator resides in the passenger compartment of the helicopter collecting data in real time.

The ARDIMS provides two unique capabilities; mapping of radiation fields and location and identification of radioactive sources. The data aids in the refinement of plume modeling. These models enable accurate sample collection at locations such as nuclear reactors and waste storage facilities. The current isotopic identification capability of the ARDIMS is limited due to the poor energy resolution of NaI(Tl) detectors. In addition, the lithium-loaded glass fiber neutron detectors are not capable of any energy binning and only provide a gross neutron count rate in neutrons per second (nps).[2]

The goal of this detector study is threefold:

1. Explore the possibility of utilizing a thallium-activated cesium iodide CsI(Tl) material due to increased energy resolution
2. Explore the capability of isotope identification by CsI(Tl) at distance
3. Compare the capabilities of CsI(Tl) with the gold standard of gamma spectroscopy – HPGe

II. Methods

The 20th utilized Monte Carlo N-Particle Code 6.2 (MCNP®), developed by Los Alamos National Laboratory, to model and compare detector materials. The source term consisted of a variable-energy, isotropic, point, photon source. The photon source energy distribution was based on a 69.8-hour background measurement collected indoors at Aberdeen Proving Ground, MD. The background was collected with an ORTEC DetectiveX HPGe detector. The distribution was discretized into 16,384 energy bins from 0 to 2 MeV. Two industrial sources were superimposed on this background as sources. Cesium 137 and cobalt 60 were selected due to their relative ease of access as industrial sources and potential use in a salted nuclear device.

The detector medium and air volumes were adjusted for successive simulations. A spherical detector geometry reduced computational time due to total encapsulation of the source in 4π. This greatly reduced the number of generated particles that did not contribute to detector counts. In addition, it allowed for significant down scatter from atmospheric effects. The detector medium thickness was a compromise between an infinitely thick detector and a detector that would allow for backscatter. The Gaussian Energy Broadening (GEB) values study utilized a 1 cm thick detector crystal.[3] We employed a similar 1 cm thick detector in an effort to maintain consistency with this previous study.

A mention of the GEB function must be made due to its usefulness in this study and to other MCNP users. The effect of GEB in MCNP is to effectively smear photon counts in the pulse-height light tally with anticoincidence (FT8) across multiple energy bins depending on the physical material qualities of a detector. The end result is a full-width half max (FWHM) of only 3-4 eV for photon detectors such as HPGe and large FWHM of upwards of 80 keV for photon detectors such as NaI(Tl). The resulting FT8 tallies energy are based on sampling from the Gaussian.[3]

$$f(E) = Ce^{-((E-E_0)/A)^2} \quad (1)$$

where E is the broadened energy; E_0 is the unbroadened energy of the tally; C is a normalization constant and A is the Gaussian width. The Gaussian width is related to FWHM by[3]

$$A = \frac{FWHM}{2\sqrt{ln\ 2}} \quad (2)$$

where the FWHM is specified based on user provided constants, a, b, and c which have been experimentally calculated in additional studies referenced in Table I.

$$FWHM = a + b\sqrt{E + cE^2} \quad (3)$$

In the above equation E is the incident gamma energy in MeV, *b* units of $MeV^{1/2}$, and *c* units of MeV.[1] The following values of *a*, *b*, and *c* were used for simulations in this study.

Detector Material [4][5][6]	*a*	*b*	*c*
NaI(Tl)	-.0024	.05165	2.85838
CsI(Tl)	.0286	.0279	.746793
HPGe	.000586828	.000395113	.746793

Table 1 GEB Constant Values

All simulations included 1.00 m of dry, near sea level air on the backside of the detector sphere to allow for potential backscattered photons. The air consisted of the following atomic fractions carbon 0.00150, nitrogen 0.784431, oxygen 0.210748 and argon 0.004671 [6]. Simulations 13 through 15 included a 25mm thick aluminum alloy 6061 sphere in order to investigate the impact of internally mounted detectors [6]. Internally mounted detectors would allow for use in multiple airframes. Currently, the 20th CBRNE is limited to the UH-60L Black Hawk as no other variants of the platform possess mounting pylons.

The typical frame of a UH-60 consist of a 4 in (102 mm) thick honeycomb aluminum alloy mesh sandwiched between two 2.5 mm aluminum alloy sheets. The thickness of aluminum alloy between the detector and the ground will vary significantly based upon the angle of attack of the aircraft. Future studies should examine the impact of this angle of attack by utilizing a repeat mesh lattice structure and then varying the location of the source relative to the orientation of the mesh.

The ARDIMS typically operates at 100 meters above ground level (AGL). It may drop below this AGL in order to conduct isotope identification. These distances were represented with 10 m or 100 m of air in simulations. An interior dark blue sphere represented the air (10 m or 100 m in thickness depending on the AGL). The air volume was surrounded by a thin black line. This thin black line represented the detector medium. The detector medium was followed by 1 meter of exterior air (green). This exterior air allowed for significant backscatter into the detector medium. The final graveyard universe was light blue. The aluminum alloy 6061 was then imposed between the interior air and detection medium to represent the hull of the UH-60L Black Hawk. MCNP simulations, graphically generated in Xming, are below in Figure 1.

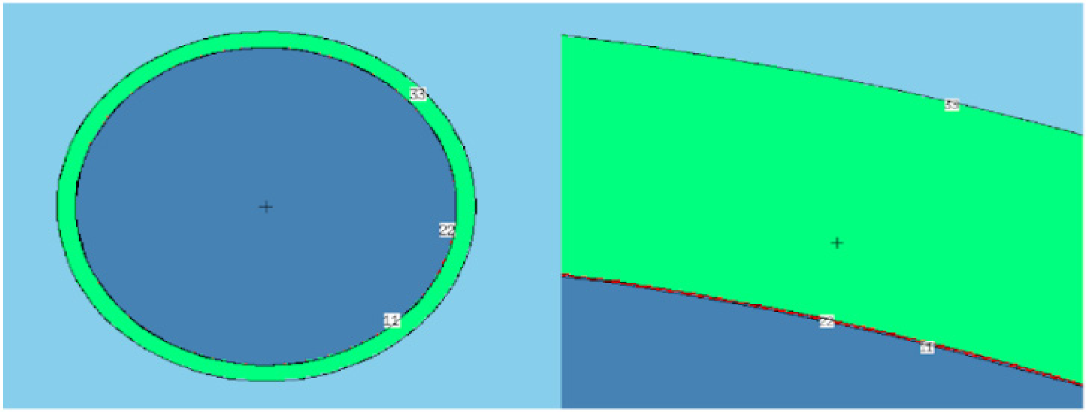

Figure 1. Xming generated visual representation of the simulation in MCNP6.2 differing colors refer to the unique materials with the source at the center of the sphere

A total of 15 simulations were generated to support proper comparison of capabilities. Below is a list of all simulations and their specifications:

Number	Description	Number of Particles Simulated (NPS)
1	NaI(Tl) 10 meters background	1E9
2	NaI(Tl) 10 meters	1E9
3	NaI(Tl) 100 meters background	1E9
4	NaI(Tl) 100 meters	1E9
5	CsI(Tl) 10 meters background	1E9
6	CsI(Tl) 10 meters	1E9
7	CsI(Tl) 100 meters background	1E9
8	CsI(Tl) 100 meters	1E9
9	HPGe 10 meters background	1E9
10	HPGe 10 meters	1E9
11	HPGe 100 meters background	1E9
12	HPGe 100 meters	1E9
13	HPGe 100 meters background Airframe	1E9
14	HPGe 100 meters Airframe	1E9
15	HPGe 10 meters Airframe	1E9

Table II: MCNP Simulations

Following simulations error was propagated utilizing the following formula for standard deviation,

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N}} \quad (4)$$

All error bars presented in the results section of this work are 2σ confidence intervals. All 15 simulations passed MCNPs standard 10 statistical checks. Runtime for each simulation averaged 270 minutes on an i9-10885H CPU @ 2.40GHz, 2400 MHz with 8 cores. MCNP multithreading was available for these simulations substantially saving on runtime.

III Results

The thallium-doped sodium iodide scintillator in the ARDIMS established a baseline for detector materials. As expected, the FT8 tally provided limited energy resolution. The 662-keV energy peak from Cs-137 is identifiable at 10 m and 100 m. At both distances, it rose beyond the associated uncertainties of the measurements of background.

The weaker Co-60 gamma peaks of 1,173.2 keV and 1,332.5 keV did not rise sufficiently to separate from the background uncertainty at 2σ. Co-60 was given a source strength of approximately 35% of Cs-137 in the source card of the input deck. Throughout all measurements, the impact of 90 meters of additional atmosphere is evident in the resulting attenuation of low-energy gammas. This attenuation was expected.

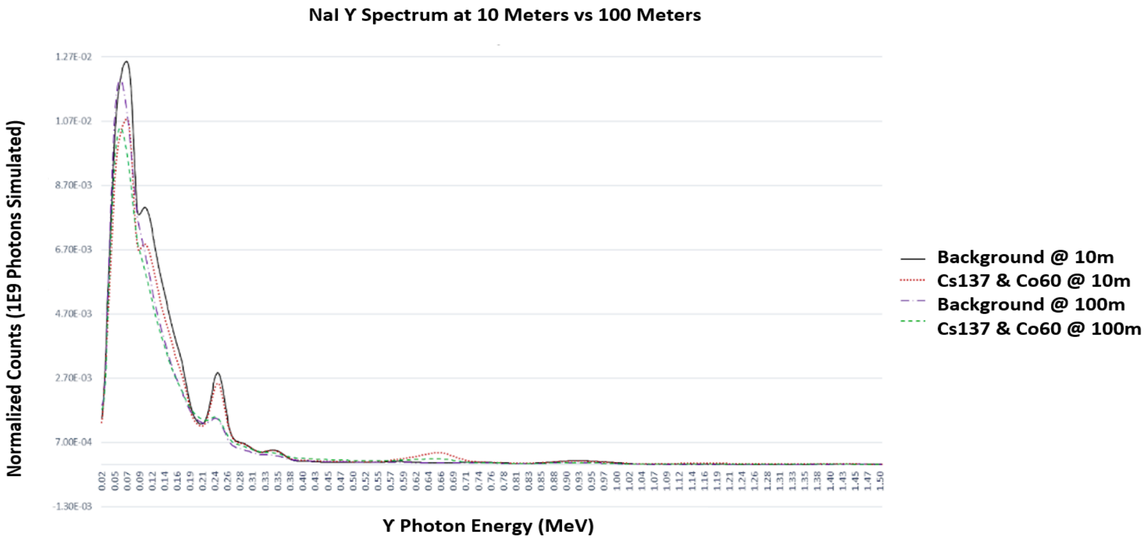

Figure 2. NaI(Tl) gamma spectrum (0 to 1.5MeV) at 10 and 100 meters with and without Cs-137 and Co-60 sources.

Note there is a slight 662 keV peak in the background measurement of Figure 2. This abnormality in the background measurement is the result of a Cs-137 check source (.50 µCi) located in an adjacent room. This peak is a slight abnormality that one would not expect to see in a background measurement in a facility devoid of radioactive material. However, in a larger facility there would be many radiation sources and variations in background are expected.

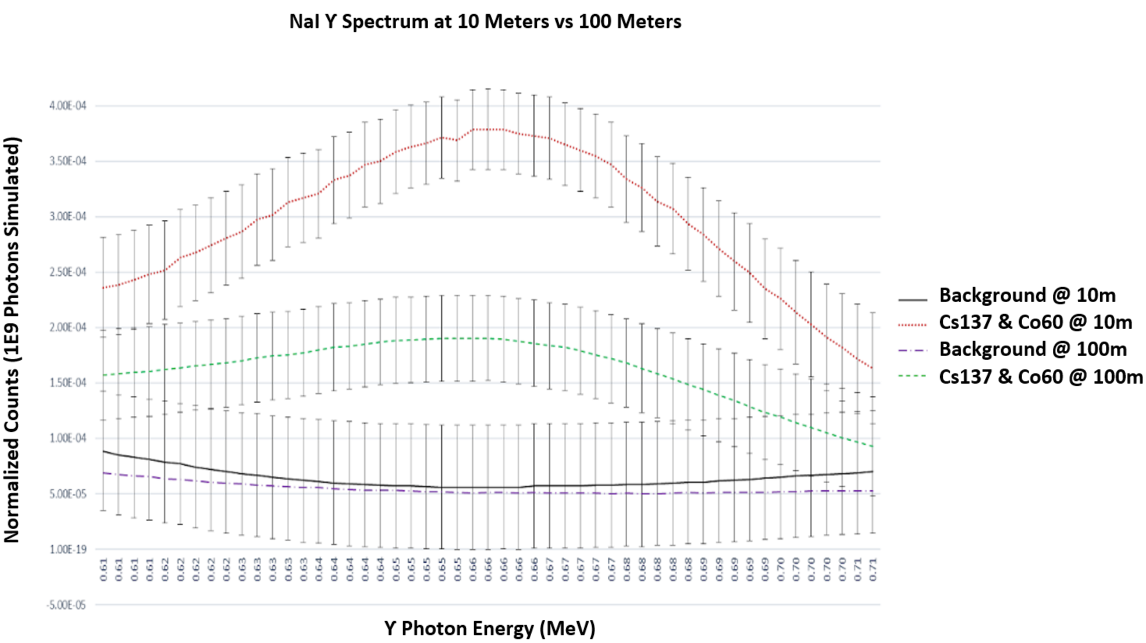

Figure 3. NaI(Tl) gamma spectrum (661 keV to 711 keV) at 10 m and 100 m with and without Cs-137 and Co-60 sources.

Cs(Tl) yielded similar results. As expected the FT8 tally provided some improvement to energy resolution. The 662 keV energy peak from Cs-137 was identified at both altitudes. It clearly rose beyond the associated measurement uncertainties. Again, the weaker Co-60 peaks did not rise sufficiently to separate them from uncertainties of background measurements at 2σ. However, there was a noticeable decrease in the FWHM. In the case of the 10 m measurement, the FWHM was 115 keV for NaI(Tl) vs. 87 keV for the CsI(Tl) detector.

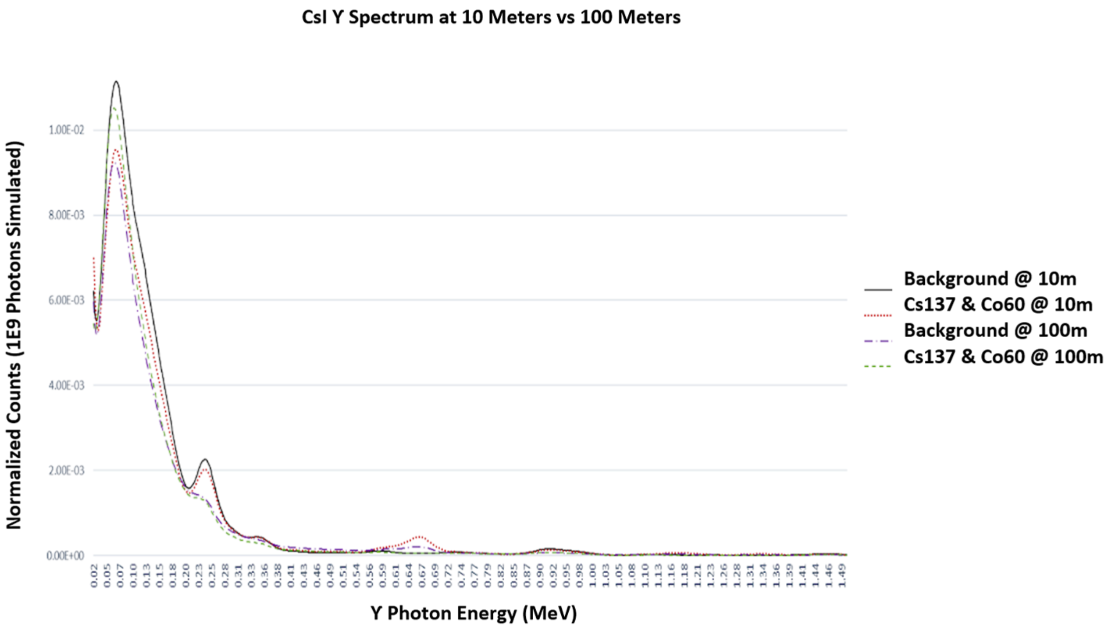

Figure 4. CsI(Tl) gamma spectrum (0 to 1.5 MeV) at 10 m and 100 m with and without Cs-137 and Co-60 sources.

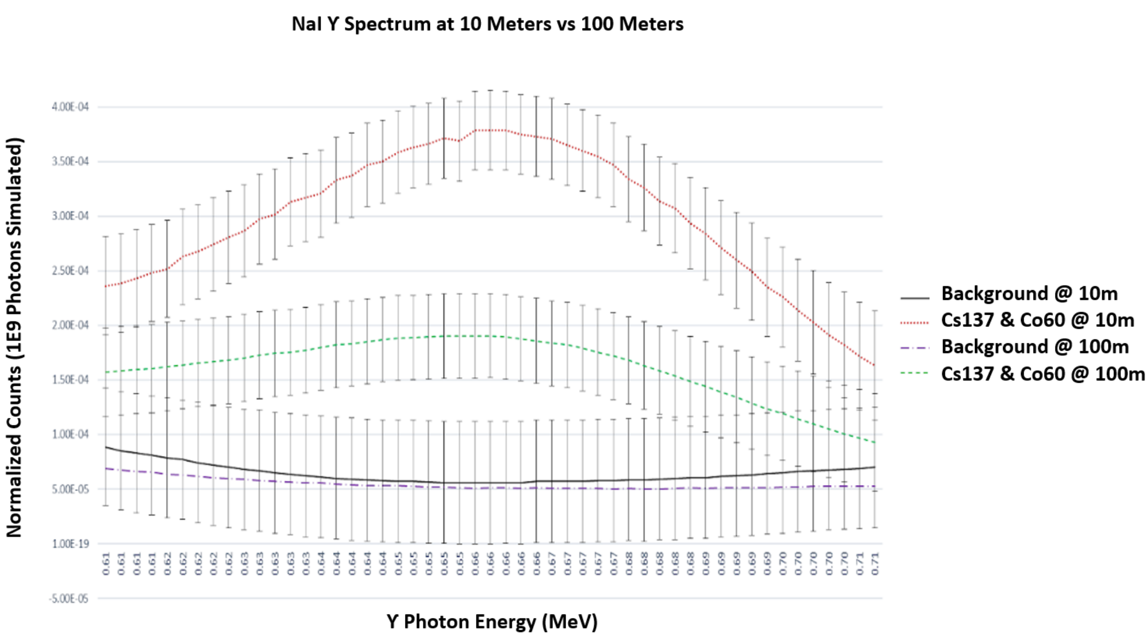

Figure 5. CsI(Tl) gamma spectrum (609 keV to 708 keV) at 10 m and 100 m with and without Cs-137 and Co-60 sources.

HPGe yielded improved results. There were notable increases in energy resolution at all energies. At 662 keV the FWHM was less than 4 keV. The known value for the FWHM at 662 keV for HPGe is 1.8 keV [7]. The difference is a result of the energy bins coded in MCNP. All energy peaks are statistically significant and visible at both 10 and 100 meters. A side effect of increased energy resolution was an increase in simulation time. More particles had to be simulated in order to fill each energy bin to a sufficient level to pass all statistical checks. This is a direct result of the minute broadening associated with HPGe. Sufficient resolution to evaluate CsI(Tl) vs NaI(Tl) was provided with 2-keV energy bins.

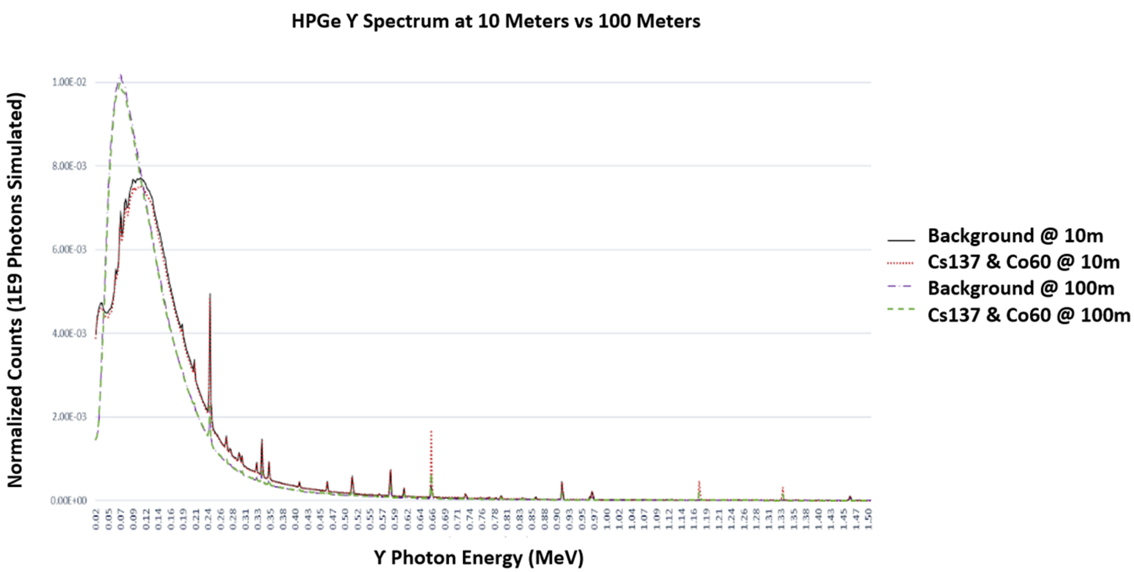

Figure 6. HPGe gamma spectrum (0 to 1.5MeV) at 10 and 100 meters with and without Cs-137 and Co-60 sources.

The excellent energy resolution of HPGe was lost when an aluminum alloy airframe was introduced into the simulation. At 100 meters there are no statistically significant peaks identifiable at any energy. In Figure 7 this was evident as the airframe peak in blue barely rose above the background count rate with the airframe (orange). Only in the unobstructed (yellow) measurement is there a statically significant 662 keV peak.

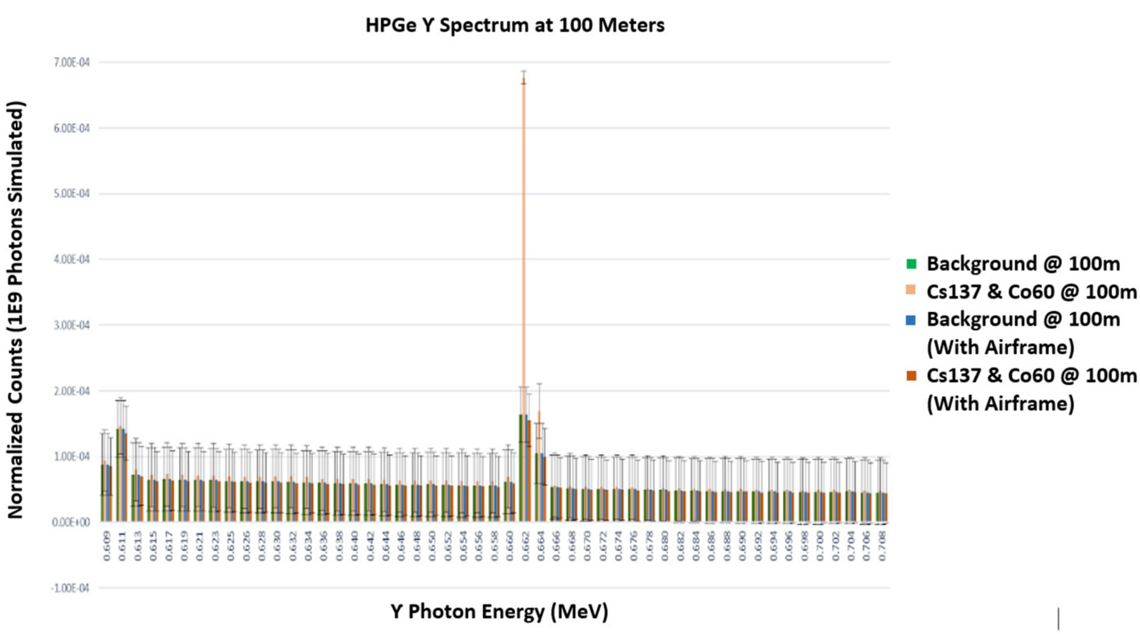

Figure 7. HPGe gamma spectrum airframe obstructed at 100 meters (609 to 709 keV)

At 10 meters all energy peaks are statistically significant and visible despite the inclusion of the aluminum airframe. The brown peak in Figure 8 clearly rises above the background measurement in blue. This information is extremely useful as it allows for refinements in the employment of an upgraded ARDIMS system.

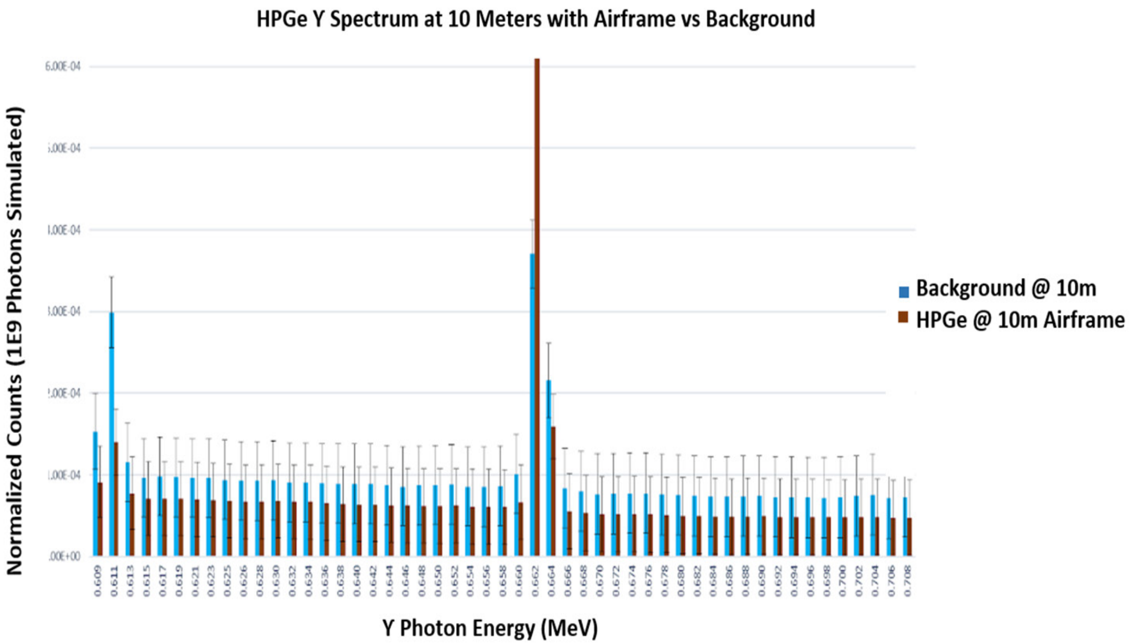

Figure 8. HPGe gamma spectrum airframe obstructed at 10 meters (609 to 709keV)

IV Discussion

As a Forces Command (FORSCOM) unit, the 20th CBRNE is concerned with developing employment practices of an upgraded system. The ARDIMS is routinely utilized for wide-area, gross-exposure collection. It has not been utilized for gamma spectroscopy and general characterization as NaI(Tl) has poor energy resolution. With an upgrade to CsI(Tl) there is a potential to utilize the ARDIMS for characterization as well as wide area plume mapping.

This upgrade would enable facility characterization. The speed of an airborne characterization system would allow the 20th to recon multiple facilities by air in the time it currently takes to travel to one facility by ground. This would allow the 20th CBRNE to quickly refine targets of interest in a radiologically diverse, large space such as a national laboratory complex.

V Conclusion

While HPGe detectors possess the best energy resolution, current crystal growth technology prohibits their employment in large detectors. This study supports the replacement of NaI(Tl) detection medium by a CsI(Tl) medium for use in the ARDIMS. The increased energy resolution, physical resilience, and absolute efficiency of CsI(Tl) detection medium make it an ideal aerial detector material. This upgrade would enable the ARDIMS to become a valuable tool for facility reconnaissance. As an added benefit it may be internally mounted in an aircraft increasing the number of platforms available for system integration.

VI Acknowledgement

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Notes

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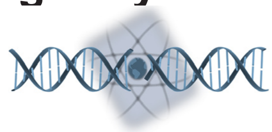
Harnessing the Environment to Identify Nuclear Processes: Biologically-Mediated Approaches



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Abstract

According to the 2018 Nuclear Posture Review (NPR), recent developments in threat networks across the globe have generated an unprecedented range and mix of chemical, biological, radiological, and nuclear capabilities that significantly increase uncertainty and risk, especially within the nuclear regime. Monitoring for nefarious activity can, in principle, take place during any process associated with the nuclear fuel cycle and encompasses a variety of methods, ranging from high-resolution satellite photography to radiological detection, that provide information at different levels of granularity. Whereas traditional methodologies remain critical for certain monitoring scenarios, they are not easily adapted for identification of clandestine stocks and covert production processes that have become more prevalent in the present threat landscape. New monitoring challenges require innovative solutions which are more than just a refinement of currently available technologies.

Biologically-based and/or –enabled technologies can provide the revolutionary improvements necessary for meeting U.S. and global nuclear security goals because of the unique capabilities they offer, including hyperaccumulation and storage of notable signatures, responsiveness to low concentrations of environmental changes and persisting integration, strong and discernible reactions that can result in easily observable changes, transient or persistence of responses, resilience to environmental insult, covert/low-visibility detection, built-in sample preparation, extremely low power consumption, and, often, low cost as compared to other monitoring methods. Biosystems can be used as orthogonal means for monitoring to augment existing technologies or could provide wholly novel approaches for identification and characterization of illicit nuclear facilities and processes. Detection schema for which biological systems or derivatives thereof can be useful to traverse concepts of operation (CONOPS) across the nuclear activity spectrum. These include both pre- and post-detonation scenarios as well as a variety of signatures including radioisotopes, heavy metals, chemicals, and biological changes uniquely associated with exposure to contaminants resulting from nuclear activity. The "Bionuclear" approaches can be grouped into three overarching categories: (1) biological markers to assess environmental exposure, (2) biological recognition elements for biotic-abiotic hybrid detection platforms, and (3) enabling technologies. Principle concepts and examples of each are provided herein for proof-of-concept. More depth in terms of approaches, signatures, use cases, and technical maturity will be provided in three subsequent technical papers complementary to the present overview.

Introduction

According to the 2018 Nuclear Posture Review (NPR), threat networks across the globe have generated an unprecedented range and mix of chemical, biological, radiological, and nuclear capabilities.[1] The NPR states that recent developments have produced increased uncertainty and risk, especially within the nuclear regime:

"…global threat conditions have worsened markedly since the most recent 2010 NPR, including increasingly explicit nuclear threats from potential adversaries. The United States now faces a more diverse and advanced nuclear-threat environment than ever before."

Nefarious actors in the post-Cold War era have a range of motivations, capabilities, and approaches for acquisition of nuclear weapons, and actual or potential increases in nuclear capability of existing states and non-state actors have significantly altered the modern threat space.[2] Cooperative regimes generally agree that nuclear weapons capabilities should not propagate to additional entities unchecked for obvious reasons. As such, monitoring and characterization of materials associated with the nuclear fuel cycle or nuclear weapons production is critical for assessing nation status and/or non-state actor intentions, capacities, and status. In a world of highly adaptive proliferators, it is necessary to continuously test and validate the informational yield of extant monitoring capabilities.

Monitoring for WMD activity includes a variety of methods, ranging from high-resolution satellite photography to radiological detection, that provide information with varying degrees of resolution. Traditional methodologies remain critical for certain monitoring scenarios (e.g., identification of new missile silos, close-range detection of special nuclear materials, analysis of effluents from nuclear facilities, inter alia), but they are not easily adapted for persistent monitoring, and identification of stocks and production processes that have become more prevalent in the present threat landscape.[3,4]

Addressing new monitoring challenges require novel solutions which are more than just a refinement of currently available technologies. Biologically-mediated solutions can provide a revolutionary improvement necessary for meeting U.S. global nuclear security goals because of the unique capabilities they offer. Such capabilities include hyperaccumulation and storage of notable signatures, responsiveness to low concentrations of environmental contaminant, strong and discernible reactions that can result in easily observable changes, long integration times, persistence of responses, resilience to environmental insult, covert/low-visibility detection, built-in sample preparation, extremely low power consumption, and, often, low cost as compared to other monitoring methods. Biosystems can be used as orthogonal means for monitoring to complement existing techniques or can provide wholly novel approaches that supplant conventional techniques. The notable advantages that biological systems confer along with the current push toward biotechnological advancement lend confidence to the supposition that biomonitoring will play a significant role in identifying illicit nuclear and other processes associated with the development and use of weapons of mass destruction (WMD).

Background

<u>Monitoring Requirements</u>

Nuclear monitoring requirements are captured in various strategies, policy documents, and treaties, many of which call for enhancement to the U.S. nuclear monitoring regime through a sustained program of research and development. For example, the U.S. Department of State funds research to develop methods for compliance with nuclear nonproliferation treaties such as the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). Nations that sign this treaty are:

"…expressing their support for research, development and other efforts to further the application, within the framework of the International Atomic Energy Agency safeguards system, of the principle of safeguarding effectively the flow of source and special fissionable materials by use of instruments and other techniques at certain strategic points…" [5]

Other U.S. government organizations, such as the U.S. Department of Defense (DoD), the U.S. Department of Energy (DOE), and the U.S. Department of Justice (DOJ) are tasked with similar mission goals to develop capabilities for safeguarding nuclear materials, monitoring weaponization and proliferation activities, and verification of treaty compliance. Many of these requirements are publicly available.

<u>Extant Monitoring Capability</u>

Many of the processing steps associated with the nuclear fuel cycle (Figure 1) can be monitoring targets for nefarious activity, and a variety of methods provide information at different levels of granularity. Storage facilities (bunkers) for weapons and materials are recognized targets for detection using methods such as high- resolution satellite photography, and satellite-, ground-, and sea-based sensors that gather real-time information on sites of interest. Mining milling,conversion, enrichment, and fabrication produce a suite of signatures for which detection motifs include point detectors, human-portable radiological detection systems, and operator-guided platform radiological detection systems, among others. Such surveillance methods can be augmented by human intelligence, and collection of samples from suspect sites can be taken to a laboratory for analyses that determine if signatures are indicative of proliferation activity.

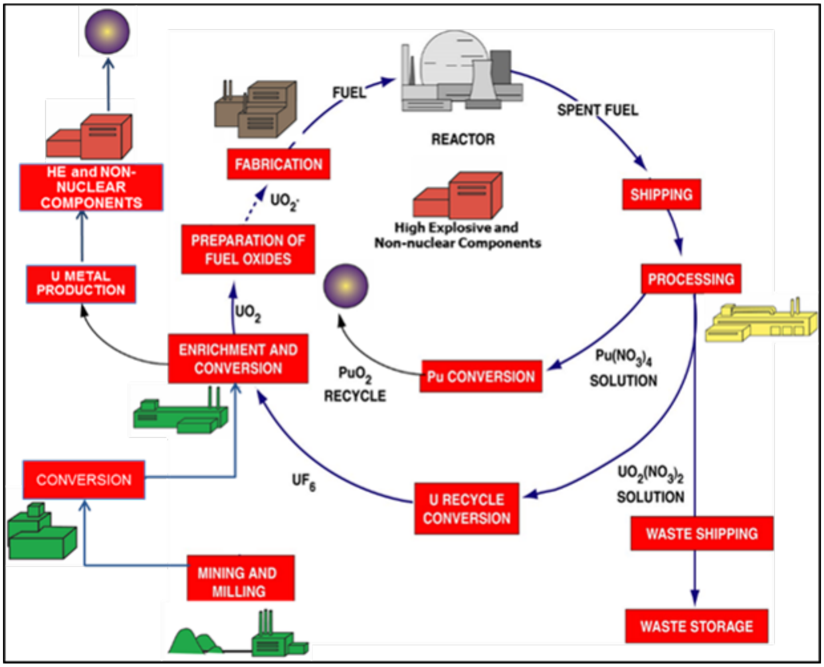


Figure 1. Overview of Nuclear Fuel Cycle (Credit: Oak Ridge National Laboratory)

Current methods for monitoring nuclear weapons testing are conducted in accordance with the verification regime of the Comprehensive Test Ban Treaty Organization (CTBTO). The CTBTO lays the technical groundwork for the global verification regime, including the use of 321 monitoring stations of the International Monitoring System (IMS) intended to be fully operational and interconnected to provide objective intelligence. IMS monitoring stations detect radioactive plumes from atmospheric explosions or those vented by underground or underwater nuclear explosions. Confirmatory analyses take place in IMS laboratory environments, where physicomechanical methods are used to identify specific isotopic signatures. IMS system sustainment requires not only the straightforward maintenance of existing capabilities, but also includes enhancement and replacement of current equipment with newly evolved technologies.[6]

Extant Monitoring Challenges

Current technologies emerged from an era when fundamental nuclear knowledge was limited to a few select nation-states. Today, access to ubiquitous information increases the likelihood that others who have interest in building nuclear capabilities will find means to do so. Availability of "nuclear knowledge" also can lead to subsequently more sophisticated methods of denial and deception that thwart attempts to gather information using traditional means of monitoring.[3]

As indicated in the previous section, nuclear monitoring capabilities include a range of approaches, such as satellite imagery, human intelligence, radiation detection technology, nuclear forensics techniques, and laboratory diagnostics for environmental sampling. Coarse-grain detection and sampling methodologies can identify the presence of radioactive contaminants in the environment that may implicate a particular process in nuclear fuel cycle; however, such methods are often ill-suited to provide descriptive information necessary to identify covert activities, particularly those taking place in apparently legitimate facilities (e.g., process diversion for uranium enrichment). Point sensors and air collection devices currently employ a number of suitable modalities, but such technologies are only useful for confirmation of a limited number signatures for which they were originally designed. Such sensing systems lack portability and have little utility for missions where near-field (less than 1 km) and mid-field (1 km to 10 km) access is not available. Moreover, currently available field-portable detection technology suffers from low selectivity and cross-reactivity with benign signatures that result in a high incidence of false positives.

Current systems are limited in their capabilities to identify, in real time or near real- time, nuclear constituents present in low environmental concentrations. Instrument sampling often requires concentrated volumes of air or water and requires long analysis times to obtain results. Prior to sample collection, signatures are subject to environmental fate and transport mediated by biogeochemical and meteorological processes. This results in a specific challenge for far-field monitoring methods (greater than 10 km) because the combination of biotic and abiotic conditions that can change the nature of the signature, the availability for sampling, and the environmental matrix in which it may be present.

Finally, whereas the majority of signatures are discussed here in the context of adversarial anthropogenic activity, it is important to note that radioactivity is ubiquitous in the natural environment. Terrestrial and cosmic sources of radiation can confound our ability to detect illegitimate processes, as can activities associated with beneficial uses of radioactive material such as nuclear medicine, agriculture, research, and energy production. Similarly, chemical signatures associated with nuclear activities can be generalizable to many industrial processes. The need for sophisticated devices to precisely monitor for presence, quantity, and specific manifestation of signature is clear. Such devices will provide a basis for discernment between legitimate and illicit activity.

Bionuclear: An Interdisciplinary Concept

Recognizing the technical gaps in extant methods and the potential revolutionary approaches that can be brought to bear by the rapidly advancing life sciences and biotechnologies, an interdisciplinary team of subject matter experts from the life and physical sciences as well as relevant engineering disciplines, came together and formed the Bionuclear Working Group (BNWG) in 2012. The key motivation of formulating the BNWG is to promote research and steer development of biologically centered approaches for environmental collection and/or detection of illicit nuclear materials and processes.[7] The BNWG addresses the importance of maintaining partnerships across academia, private industry, and government to address such needs by maintaining a community of practice whose role is to actively engage and build collaborations among researchers and stakeholders within the Department of Defense (DoD) and multiple other US government agencies – an Interagency community. As technology advances and becomes more available to those who conceive novel means to compromise global nuclear security, it is of utmost importance to maintain an adaptive state of scientific defense. The BNWG has adopted the unique position of aggregating scientific research that bolsters nuclear security while sustaining an ecosystem of innovation for the public good. The content provided herein is from a series of meetings and workshops, to discuss progress in a broad range of research areas, to share development opportunities with the research community, and to explore the feasibility of proof-of-concept solutions.

Multiple U.S. Government (USG) agencies are presently funding research and development to support biomonitoring efforts that are carried out by the academia, research institutions, DoD Service Laboratories, and the U.S. Department of Energy National Laboratories. In addition, the USG recently bolstered its investment in biotechnology through the creation of large programs specific to DoD needs, including BioMADE (biomade.org), BOOST (https://www.defense.gov/News/Releases/Release/Article/2600172/department-of-defense-announces-fy21-boost-program-awardees/), TRANSFORME (https://www.arl.army.mil/opencampus/TRANSFORME), and White House initiatives (https://www.whitehouse.gov/wp-content/uploads/2020/08/M-20-29.pdf, https://irp.fas.org/offdocs/nsm/nsm-1.pdf, https://irp.fas.org/offdocs/nsm/nsm-1.pdf). Further, organizations like the BioFabUSA Institute (https://www.manufacturingusa.com/institutes/biofabusa) support public-private partnerships for development of high-impact biotechnologies. The aforementioned efforts provides a means for U.S. manufacturers to retain a competitive edge in domestic technology and supply chain capabilities.

<u>Bionuclear Concept</u>

The term “Bionuclear” was coined to reflect an interdisciplinary development that is focused on adapting and developing modern life science principles and biotechnologies to strengthen nuclear detection, monitoring, and characterization capacity. It refers to the contextual use of intact living systems, biological components, biological pathways, or biological networks to detect, identify, and/or characterize undeclared fissile material production, movement of fissile material, or nuclear tests through signature exploitation. Working definitions associated with the aforementioned and related to common themes throughout the present document include:

- Living systems are single-celled (e.g., bacteria, yeast, algae, archaea) and multicellular organisms (e.g., plants, animals, complex fungi) with representation from both prokaryota and eukaryota.
- Biological components include tissue and other structural compartments, macromolecules, intra- and extracellular structures, and biomanufactured materials (e.g., tissue cultures, artificial skin).
- Biological pathways include genetic and epigenetic regulatory pathways, metabolic pathways, and signal transduction in living systems.
- Biological networks range from interactions among subcellular biochemical pathways to more complex interactions between cells and among communities within an ecosystem.
- Signatures include (1) fissile and non-fissile materials generated as a result of nuclear production processes and other components or constituents (e.g., heavy metals, industrial chemicals) that do not include radioactive materials but may be indicative of said processes, and (2) the measurable biological responses, whether at the whole organism, cellular, or subcellular level, that occur as a consequence of exposure to the conventional signatures delineated above.

Bionuclear Approaches to Addressing Extant Capability Shortfalls

Many of the available nuclear detection and monitoring technologies have hit an asymptote in terms of their utility for specific concepts of operation, and additional device engineering is expected to yield minimal results. In contrast, applications of biology and bioengineering to monitoring needs have been only partially explored and their distinctive properties may offer truly pioneering solutions. Although more research is needed to fully incorporate biological systems into nuclear monitoring toolkits, their untapped potential as well as notable successes in monitoring for general ecosystem health merit the investment.

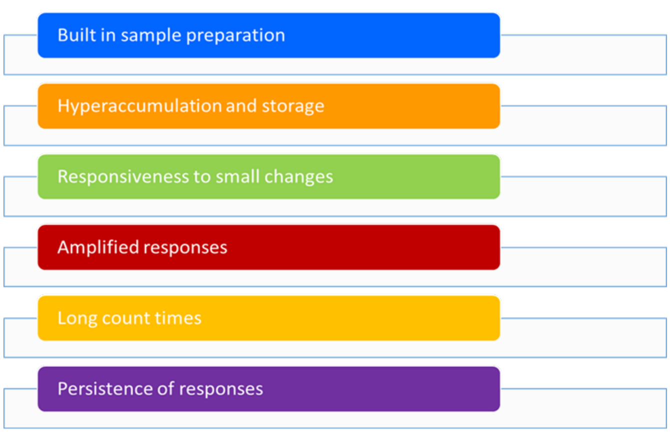


Figure 2. Living systems have a number of distinguishing qualities that make them "naturally" useful for monitoring.

A wide range of flora and fauna respond to environmental changes in their surroundings, and act as natural pre-concentrators by continually collecting and concentrating materials from the environment. Collection and analysis of biomaterials from known concentrators can supplement or replace other forms of analysis, particularly where mobility in soil and water matrices typically results in loss of signature. Biochemical, genetic, and other changes to biota in matrices which are routinely sampled could indicate the presence of contaminants. For example, functional and community-level changes to microbiomes in water (e.g., marine and freshwater systems, wastewater), soil, and sediment could provide information on periodic or chronic presence of environmental stressors associated with suspect nuclear processes. Other approaches may include the manipulation/manufacture of specific biosystems or their components to create new detection motifs that meet necessary size, weight, and power requirements for non-cooperative monitoring. Natural systems possess unique advantages, which include the detection of radioisotopes and chemicals from various effluent sources, for field deployments and, in some cases, naturally discriminate radioisotopes through metabolic and chemical coordination processes. The vast majority of biosystems do not require complicated emplacements nor do they require access to power grids. Biologically-enabled systems can be specifically engineered to minimize the need for human intervention and are suitable for relatively long-term field deployment in many environments of concern.

Research efforts endorsed by the BNWG focus on living systems that act as or enable development of collection and detection systems for radioactive residues, industrial chemicals, heavy metals, changes in metabolic profiles, and/or other distinctive biological changes associated with exposure to radionuclear contaminants or environmental proxies. Development of monitoring systems that combine the attributes of selectivity, sensitivity, and durability while providing information allowing for dosimetric, temporal, and positional reconstruction of nuclear events is the fundamental aim.

Technical Categories

Detection schema for which biological systems or derivatives thereof can be useful traverse concepts of operation (CONOPS) across the nuclear activity spectrum. A structure emerges when applications are considered as interlinking technical categories that address multiple CONOPS. Application-based categories are subsumed into a framework that reveals three overarching groups:

- **I. Biological markers to assess environmental exposure**
- **II. Biological recognition elements for biotic-abiotic hybrid detection platforms**
- **III. Enabling technologies**

Each of the above constructs will be discussed in greater detail in a short series of forthcoming technical papers, but brief descriptions are given herein for the purpose of providing context.

I. Biological Markers to Assess Environmental Exposure

Anthropogenic nuclear activities often result in environmental release of ionizing radiation, radionuclides, organic chemicals, inorganic ions, and heavy metals in various forms. Exposed organisms

Figure 3. Organisms in all environmental compartments are constantly gathering information about their surroundings.

respond to such environmental perturbations when stressed above species-specific thresholds and can provide valuable insight regarding the particulars of the nuclear process.

Biological markers that can contribute to development of novel monitoring solutions are too numerous to recount in a single articulation, but examples include:

Microbial Species:
❖ Soil, water, air, and plant microbiomes
❖ Extremophiles
❖ Biofilms
Multicellular Organisms and Biologically-Derived Materials:
❖ Vegetation
❖ Native and Domesticated Animals
❖ Humans
❖ Biological Materials
Ecological Networks:
❖ Mycorrhizosphere

Table 1. Examples of biological systems and networks that can contribute to monitoring solutions.

The primary strength of the denoted architectures lies in their ability to act as "collection systems" that can sequester signatures of interest or retain a molecular imprint of the interaction. Such systems are useful for signatures whose environmental fate and chemistries render them inconclusive at the time of collection or whose mobility in environmental matrixes make them difficult to capture unless collections occur immediately upon release. In most cases, the likely means of retrieval will be via laboratory analytics; however, some may be amenable to remote interrogation through the application of various imagery or spectral techniques.

Microbial Species and Communities

Soil, Water, Air, and Organismal Host Microbiomes. Soil, water, air, and organisms host a variety of microscopic life forms ("microbiomes") for which genomic, biochemical, and trait-based data are accessible.[8] Microbiomes are composed of thousands of microbial species intricately linked to each other, and to the health and functioning of systems in which they reside. Microbiome community composition is a consequence of the dynamic interplay between the resident species and the local environment.[9] Environmental changes can induce selective pressures which result in potentially measurable shifts to species composition and density as well as expression of characteristic traits (e.g., particular protein isoforms) even where the specific taxa may vary from site-to-site.[10] End-state community structure can be somewhat predictable, given the nature of the exogenous stressor, as is demonstrated, e.g., by interrogation of uranium mine tailings[11], industrial areas[12], and other contaminated environmental matrices.[13,14] Certain genera and, in some cases species, are characteristically present in predictable relative proportions or communities exhibit functional similarities. Further proof-of-concept is available in the biomedical realm, where health conditions such as liver disease and specific cancers are associated with the presence of particular gut and local microbiome constituencies.[15]

Collection of samples from relevant biological depots can be coupled with sequence, metagenomics, and functional analyses to determine whether the site of collection is contaminated by analytes indicative of particular processes of interest. Proof-of-principle for such approaches is amply provided in the literature, including a recent study that sought to develop an operational biomonitoring application to reliably detect episodic and low-level chronic contamination with uranium. The collaborative work between Areté Associates and Oak Ridge National Laboratory yielded a computational model that is able to discriminate between microbiome samples from contaminated versus uncontaminated areas without prior knowledge of the geochemistries of a given site.[16]

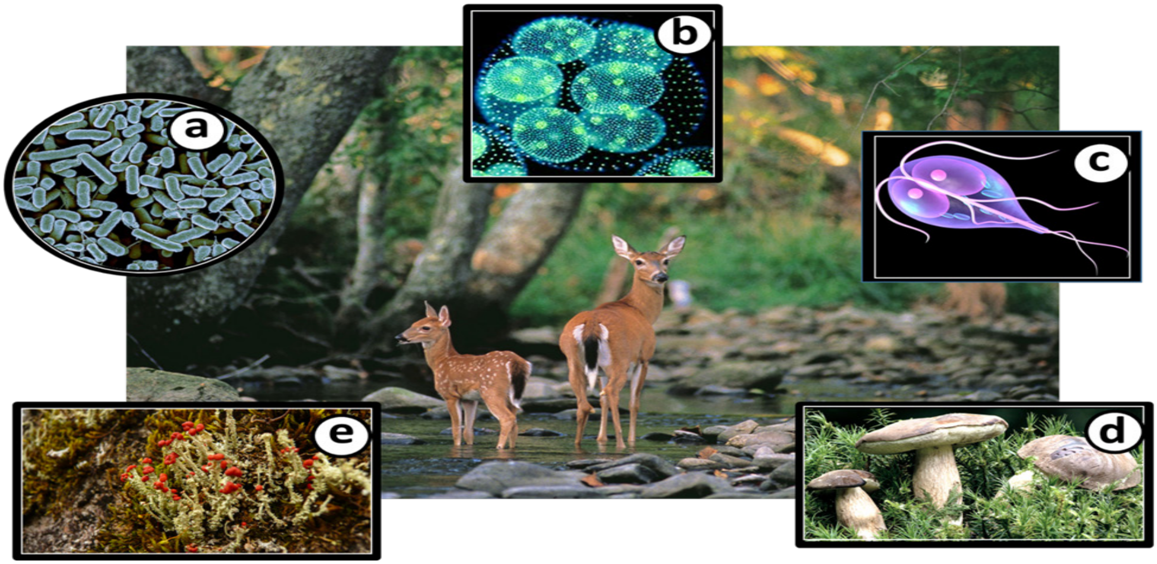


Figure 4. All living things (whales to microbes) have cellular chemistry that reacts to ionizing radiation. Considering that one gram of soil can have more microorganisms than people on earth, microbes provide an excellent opportunity for detecting the presence of ionizing radiation. The microbial world includes: (a) bacteria and archaea, (b) algae, (c) protozoans, (d) fungi, and (e) lichens. The potential to use indigenous microbes as sensors for ionizing radiation provides considerable potential for monitoring nuclear activity, largely due to their tremendous physiological versatility, ranging from extremely acidic to alkaline environments and a capability of thriving in temperatures from below freezing to above boiling.

Extremophiles. As indicated in the previous section, certain organisms may be present in the extreme environments characteristic of sites contaminated by nuclear processes. "Extremophiles" are micro-organisms that possess unique qualities allowing them to persist in extraordinarily harsh conditions. The ubiquitous presence of such microbes, in addition to their broad functional repertoires for maintaining cell viability in the presence of exogenous stressors, make them excellent candidates for novel sensing motifs. Presence of unique strains and community shifts favoring the presence of extremophiles over their less-resistant counterparts could indicate the presence of contaminants. For example, Chernobyl studies on changes to soil ecology associated with the presence of radionuclides indicate higher prevalence of resistant taxa in radiation-contaminated areas.[17] Presence of unique bacterial strains that are resistant to and can accumulate heavy metals likewise has been linked to environmental presence of toxic metals such as uranium.[18,19] Some evidence also suggests that particular stressors may impose selective pressures which cause distinctive and predictable coalescence of community structure regardless of the starting state.

Biofilms. Biofilms are tightly-coupled interdependent microbial consortia protected by macromolecular matrices consisting of proteins, DNA, and/or polysaccharides. The architectural network or biofilms provide an internal environment that both protects the community and enables communication between individual cells. The resiliency conferred by those protective networks makes biofilms attractive for use in a number of environmental and industrial applications, including sequestration of contaminants. The scientific literature is replete with references to bioaccumulation and bioremediation of heavy metals and demonstrate that microbes formulate biofilms to trap heavy metal ions in response to metal-induced stress.[20]

<u>Multicellular Organisms and Biologically-Derived Materials</u>

Vegetation. Airborne and aquatic effluent releases from nuclear processes result in deposition of material in the surrounding environment. Such material is often intercepted by vegetation and can be retained on external structures for extended periods of time, depending on meteorological conditions, plant morphology, and other factors (e.g., periodic grazing). Radionuclides contained in effluents also accumulate within plant material due to the dynamics between soil-root uptake and plant metabolism.

Sorption and uptake of radionuclides in plants has been extensively studied to evaluate depositions resulting from atmospheric tests, nuclear accidents, and nuclear energy production. Resources available to the U.S. Federal Government provide detailed information regarding specific radionuclides known to accumulate in vegetation. Isotopes of Sr (e.g, Sr-90) and Cs (e.g., Cs-137) have been the subject of significant study because of established anthropogenic origins and bioavailability, but many other radionuclides and corresponding radioisotopes (e.g., Pu-232, -246, Am-241) have also been evaluated.

The Environmental Protection Agency, U.S. Department of Agriculture, other U.S. Government Agencies, and many European entities monitor the state of vegetation in situ as well as remotely to identify impacts of pollutants, land use, and climate change, inter alia, on ecosystems. Their efforts have demonstrated that tools like machine learning can be applied to satellite imagery to identify subtle phenotypic changes such as plant size, height, growth rate, discoloration, and leaf area, thus provide proof-of-concept for use of satellite imagery to identify changes to vegetation that may be associated with nuclear activity.[21]

Native and Domesticated Animals. Animals are sensitive to environmental perturbation thus can act as sentinels of ecosystem change mediated by nuclear activity. An assortment of methods can be used to interrogate biological samples such as blood, urine, scat, and animal products collected from indigenous and agricultural systems, and such assessments provide an additional source of intelligence that would otherwise be difficult to gather.[22–24] For example, a number of biomarkers in both native and domesticated animals that can serve as biodosimetric tools to estimate low-dose radiation have been identified.[25] Assays have been developed and validated for these biomarkers which include, among others, chromosomal changes, DNA damage, transcriptional changes, and oxidative stress repair pathway activation. Proof of concept is demonstrated by, e.g., studies on inhaled uranium exposures demonstrate that urine concentrations of β2-microglobulin serve as a good proxy for yellow-cake exposure.[26] Sensitivity of the assay and the time scale post-exposure that the organism would be able to detect the signal was reported to range from 0.001 to 5 Gy and minutes to years, respectively, although, in general, longer or higher exposures provide more detectable signatures.[27]

Humans. Occupational exposure often occurs with engineers, scientists, and technicians who work with or work near fissile materials. Analyte-dependent nuclear signatures may remain intact in specific tissues for a considerable amount of time. For example, it has been demonstrated that radioisotopes could be detected in hair and nail samples from nuclear workers and that specific uranium isotopic ratios (235U/238U and 236U/238U) were indicative of exposure in occupational settings.[28] Urine, blood, and fecal samples contain recently absorbed material which can be sampled and analyzed.[29] Serum enzymes, such as amylase and diamine oxidase, may also be useful when analyzed in conjunction with routine medical examinations. The degree of genomic and proteomic expression in response to radiation has also been demonstrated as a potential method for use in human biodosimetry.[30] Metal radioisotope exposure analysis in humans has also been extended to include Cd, Cr, Pb, Zn, Al, and Cu. Prompt exposure to radiation, including radiotherapy, induces changes to human skin and oral microbiomes. Evaluation of community restructuring, changes to species diversity, and other markers associated with dysbiosis may provide an additional means to establish time and duration of exposure.[31]

Biological materials. Calcified tissues such as exfoliated deciduous teeth[32] and walrus tusks[33] are known to be exceptional lifetime integrating dosimeters through the application of electron paramagnetic resonance (EPR). EPR uses the same physics as magnetic resonance imaging (MRI).

However, MRI interrogates unpaired protons (water) in the body whereas EPR interrogates unpaired electrons, like those created by exposure to ionizing radiation, in the valence band of solid-state materials. The unpaired electrons are effectively free radicals stabilized at defect sites in the crystalline matrix and whose differences in spin states under a magnetic field can be used to quantify cumulative exposure to radiation for a given material. This allows items such as biogenic silica[34], sugars[35], and even ambient particulates[36] to serve as retrospective dosimeters.

Ecological Networks

Mycorrhizosphere. Mycorrhizae (myco–fungus + rhizo–root) are widespread networks of symbiotic nutrient and information exchange between plants and soil fungi. Approximately 80% of terrestrial plants form mycorrhizal associations. Hidden underground, filaments of fungi interlink with the root systems of plants, creating vast interspecies exchanges that distribute water, minerals, carbohydrates, and even signals of distress. Capable of relaying resources and information across whole ecosystems, these large networks of fungal interconnections have been dubbed "myconets" or "the wood-wide web".[37] Due to the sensitive interconnectivity of these fungal networks, disturbances to any one part of an ecosystem could be translated into intelligible signals distributed across the regional myconet. Responses to or signatures of environmental influx of radionuclides, processing chemicals, or ionizing radiation may be distributed throughout plants and fungi in a myconet or aerially through volatile chemicals, pollen, or spores. Fungi are also known to bioaccumulate heavy metals and radionuclides, which may lead to establishing "mycological fingerprints" as biorecognition elements for isotopes of interest.

Additional Considerations

The following criteria should be applied (after "Environmental Protection: The Concept and Use of Reference Animals and Plants"[38]) when evaluating the utility of specific organisms for biomonitoring:

- A reasonable amount of biological information is already available and can guide development of testable hypotheses regarding use as environmental indicators.
- They are amenable to future research, in order to obtain the missing or imprecise data.
- They are either ubiquitously distributed or, if indigenous, present in some abundance in particular ecosystems of interest.
- Their geographical ranges are limited and/or well-defined.
- They are likely to be exposed to radiation or proxy indicators as a result of their natural ecologies (e.g., feeding habits).
- They should accumulate and concentrate contaminants to measurable levels and, ideally, to levels higher than those present in the surrounding environment.
- Their life cycles are likely to be of relevance for evaluating contamination events from a temporal perspective.

In some instances, it will be challenging to discriminate natural variability from changes induced by anthropogenic activity, thus the utility of bioindicators in highly heterogeneous environments may be limited. In addition, changes may be influenced by other factors (e.g., life stage, desiccation, parasitism) that make it difficult to identify causal mechanisms of change. The biomonitoring field would benefit from development of consistent and standardized research methods as well as documentation of the most useful bioindicators for a given set of analytes in a particular environment.

II. Biological recognition elements for biotic-abiotic hybrid detection platforms

A wealth of research has interrogated the use of biological systems or components that can be integrated as interfacial materials in synthetic platforms.[39] The preponderance of work has been geared toward evaluating the utility of biological molecules as interfacial materials or "biological recognition elements", primarily because of their exquisite selectivities for binding specific analytes to the exclusion or near-exclusion of others. DNA aptamers, peptides, enzymes, antibodies, whole microbial cells, and many other biologically-derived motifs have been evaluated in various studies for incorporation into well-characterized sensing platforms and have demonstrated utility under certain conditions.[40] For example, glucose oxidase and catalase tied to potentiostatic platforms are shown to be effective blood glucose monitors.[41] Biological materials like those delineated above are frequently labile outside of the narrow range of conditions that promote activity in living systems. As such, more recent research efforts have sought to increase durability in a broader operational environment by using novel tethering, immobilization, encapsulation, or cell encasement strategies to ruggedize the materials and/or to provide the appropriate conditions for cell viability.[42]

To date, biologically-based and –derived sensing systems have been useful primarily in terms of biomedical and, to some extent, environmental and food monitoring applications and remain limited in their utility to address operational needs like those outlined herein. However, recent literature surveys indicate that promising advancements have been made in studies of both whole cell sensing systems and systems which incorporate enzymes and other macromolecules or structures as recognition elements.[43–45] New means of manipulating the biological components of such systems will lead to the development of novel collection and sensing devices that could eventually replace many current analytical applications. As utility for defined applications will be predicated upon factors such as specificity, storage needs, environmental stability, cost, and analyte(s) to be detected, a particular set of requirements will drive selection of one system type over another. Two generalized motifs are described below to provide proof-of-principle, but a brief survey of the scientific literature reveals numerous possibilities with regard to selection and design of biological recognition elements.

Microbes

Microbes (e.g., bacteria, yeast, microalgae) are coming into increasing use in the fabrication of biosensors, as use of whole cells confers several advantages. Microorganisms can be produced in large quantities using established culturing methods, are easy to manipulate, and exhibit great capacity to adapt to harsh conditions. Whole-cell biosensors that incorporate microbial species as interfacial materials demonstrate utility for a number of applications ranging from environmental monitoring to public health46, and several are already in commercial use. Single point/single analyte, as well as arrayed sensors which incorporate two or more microbial species, have been developed. Manipulation of cellular pathways and use of synergetic microbial consortia47 to engender multiple response types to a single analyte can provide an orthogonal means to verify the presence of a particular analyte and decrease levels of uncertainty. Genetic engineering yields production of microbial biosensors with superior ability to selectively concentrate desired analytes while excluding interferents, thus increasing signal-to-noise ratios and reducing both false positives and false negatives. Moreover, compatibility of microbial systems with commonly-used sensor platforms (notably, electrochemical and optical platforms) has been established. However, additional work remains to be done to address the basic limitations, including slow response times, variable selectivities, and sensor drift due to restructuring of microbial populations. As noted above, genetic engineering strategies can be applied to overcome system inadequacies. It is advantageous to consider the use of e.g., extremophilic species that can tolerate environments contaminated by toxic chemicals, heavy metals, and radioactive materials. Novel selective screening methods can enable the discovery of rare or unknown species that exhibit resilience in extreme environments.[48] so that integrated systems can meet size, weight, and power requirements for forward-deployed CONOPS (see, for example, Ostrov et al.[49]).

Enzymes

Because of their high specific activities coupled with high analytical specificities, enzymes are among the most commonly employed biological recognition elements. Enzymes can bind signatures of interest, including chemicals and heavy metals, while producing measurable optical and electrochemical signals. Several studies have demonstrated that incorporation of engineered reporter molecules (e.g., green fluorescent protein) can further amplify signals upon analyte binding.[50] Enzyme-based materials that change color upon contact with chemical warfare agents and other WMD have been developed. Enzymes have been incorporated into a number of different materials, including coatings[51], inks[52], and papers[53], to expand their utility and to produce novel "on demand" detection motifs. However, as previously noted, enzymes generally cannot continue to function outside of a constrained set of conditions and are prone to denature or otherwise degrade due to desiccation, temperature extremes, and presence of contaminants like ionizing radiation. New methods for interrogating enzyme-based systems, exploration of novel enzymes, and enzyme encapsulation strategies (e.g., protein scaffolds, nanotechnology substrates) for development of rugged sensing systems are clearly merited if such sensors are to be routinely used in operational environments. Recent advances in other fields, including analytical chemistry, biophysics, materials science, and computational biology, can further inform and assist in development of suitable platforms.

III. Enabling Technologies

Recent technological advances have led to an unprecedented ability to explore biology at varying levels of granularity. These enabling technologies will yield previously unattainable information and provide valuable insight that guides design of biocollection and -detection systems. Enabling technologies can also allow for the development of bionuclear sensing motifs that can be ruggedized for use in fieldable detection systems that can be integrated into future monitoring missions. Select examples are provided below but represent only a small number of the burgeoning technologies that can support the study and manipulation of biological systems. Using biological systems to estimate radiation exposure levels and track sources of exposure is a complex effort, as even closely related organisms may experience markedly different responses to radiation events.

Cryoelectron Microscopy

Cryo-electron microscopy (cryo-EM) is based on the imaging of radiation-sensitive specimens in a transmission electron microscope under cryogenic conditions and is becoming a mainstream technology for imaging cellular architecture at sub-nanometer resolution.[54] Applications of cryo-EM now span a wide spectrum in biology, ranging from imaging intact tissue specimens, individual bacteria, viruses, and macromolecules.[55] Cryo-EM has been applied successfully to analyze biological structures in many contexts, with the added benefit that it provides higher resolution and less biological perturbation than traditional X-ray crystallography.

Mass Spectrometry

Mass spectrometry (MS) is a well-established tool in systems biology that is based on the quantification of ionized biomolecules in complex cellular and environmental matrices. Advances in sample preparation, chromatography, bioinformatics platforms, and mass analyzers provide the ability to quantitate and identify endogenous biomolecules in their native states.[56] Significant effort has been put forth to rapidly quantitate small molecules in biofluids whose concentrations fluctuate upon exposure to ionizing radiation, but further work is needed to validate procedures in non-human systems.[57]

Next Generation Sequencing (NGS)

Understanding the functional annotation and metabolic potential of thousands of microbes has been made possible by NGS.[58] NGS is routinely used to determine the composition of microbial communities by amplicon sequencing, which is targeted sequencing of the 16S ribosomal RNA (rRNA) gene sequences for prokaroyotes and the 18S rRNA gene sequence for eukaroyotes. Alternatively, shotgun, or metagenomic sequencing, at single nucleotide resolution

allows for sequencing of all genes present in a sample, providing insights into community structure and function and/or shotgun sequencing at single nucleotide resolution. Metagenomics method also allow for uncultured microbial community characterization.[59] Such techniques are necessary to determine how microbiota undergo spatiotemporal changes from natural environment and due to variation in geography and seasonal processes. Benchmarking such changes with NGS is critical to detect subtle genomic and functional changes within microbial environments that are indicative of exposure to signatures of interest. NGS can be integrated with toxicogenomics to monitor changes in genes or gene expression levels in humans, animals, and plants in response to xenobiotic exposures. This approach can be used to correlate such exposures with mutational frequencies and transcriptomic perturbations, which is useful in leveraging population genetics to assess changes in contaminated sites.

Toxicogenomics

Using biological systems to estimate radiation exposure levels and track sources of exposure is a complicated effort, as even closely related organisms may experience markedly different responses to radiation events. Despite the challenges, use of toxicogenomics to characterize actually or potentially contaminated environments and to assess the impacts of exposure remains common practice within the current risk assessment framework.[60–63] New approaches in systems toxicology aim to computationally reconstruct core components of molecular-, cellular-, and organ-level networks that are perturbed because of chemical exposure. Such tools make it feasible to use large-scale data streams to develop qualitative and quantitative views of complex cellular networks. The approach could be extended to computationally recognize biological signatures of radiation exposure from a wide variety of organisms and exposure conditions.

Computational Design of Proteins

Computational design of proteins breaks the boundaries of the already massive pool of naturally evolved proteins from which biological recognition elements can be selected. Whether the protein is designed de novo or redesigned from naturally evolved structures, computational approaches can be a powerful tool for engineering protein-based biosensors. A deep learning algorithm, AlphaFold, recently predicted 3D protein structure with near experimental accuracy bolster confidence for computational design.[64]

Synthetic Biology

Synthetic biology offers the capability to create new chemistries that have challenged traditional synthesis methods. Such research crosses the gulf between chemistry and biology in a profound manner, and we are only beginning to understand the ramifications for translational uses. Genetic modification and bioengineering efforts have increased yields in protein production and have likewise created organisms with unique material production capacity. Recent synthetic biology tools have simplified organism modification from simple genetic parts to entire genomes.[65] Predictive computational modeling, in conjunction with NGS, has also dramatically shortened product development timelines.[66]

Synthetic biology can dramatically enable sensing functions in living organisms by expressing novel recognition elements or whole-cell systems that are entirely new to nature. Such processes are comprised of enzymes that are manufactured through in silico techniques from custom designs, originating from different organisms across all domains of life. Several use cases have been demonstrated.[67,68] Synthetic biology also has been used to enhance survival/persistence of sensing organisms or to enable chemical interactions within their surroundings. Although accepted for industries ranging from production of pharmaceuticals to agriculture, deployment of genetically engineered organisms and components for sensing applications requires special consideration. It will be advantageous to evaluate ethical and technical questions in parallel and throughout developmental and use stages.

Biocatalysis

Biocatalysts have been used in production processes for hundreds if not thousands of years. Synthesis of “non-natural” complex molecules via biocatalysis as opposed to traditional chemical synthesis methods offers several advantages because of the high levels of chemo-, regio-, and enantioselectivity biocatalysts exhibit. Such advantages include reduction in use of expensive chemical protecting groups, minimization of undesirable product yield, easier separations of desired products, and fewer environmental problems related to energy footprint and disposal of organic solvents.[69,70]

Biocatalysis can be used to produce polymers and other scaffold materials useful for design of novel detection motifs. Biocatalysts can improve polymer surface properties (such as hydrophilicity) and activate materials for further processing to create materials with unique architectures and functions. Likewise, whereas chemical and electrochemical methods are challenged to produce materials like conducting polymers suitable for technological applications, template-free synthesis of polyaniline has been demonstrated using an acid-resistant form of peroxidase that is compatible with operation at pHs required to produce polyaniline with the desired linear structure. Enzymes also have been used to facilitate polymerization of a broad variety of materials through transesterification and redox reactions. Proteins like calmodulin and elastin have provided the foundation for synthesis of supramolecular 3D structures with emergent chemical and physical properties, thus demonstrating the capability of enzyme-polymer hybrids to capture previously intractable analytes.[71]

Remote Power Generation from Microbial Fuel Cells

Power requirements for autonomously operating systems collection and detection systems, especially in remote and/or limited access locations, limit the useful lifetimes of such systems. Field-based power harvesting technologies can be used to charge batteries and extend the life of systems that gather, generate, and transmit data. Technologies like silicon-based solar cells provide a means to extend field activities; however, traditional solar panel designs may not be feasible in some circumstances due to size requirements and visibility. Power generation via microbial fuels cells (MFCs) offers a means to continuously generate power by tapping into the electrical activities of microbes. Within MFCs, microbes grow on an anode and utilize organic carbon as a growth and energy source. During growth, resultant biofilms transfer electrons to the anode with electron flow to the cathode for power generation. ROS generated at the cathode can be detrimental to cell growth, but biocompatible self-healing electrodes that allow hybrid inorganic/organic systems to operate aerobically were recently developed.[72] Modifications of current materials that comprise anodes, cathodes, and ion-exchange membranes can lead to dramatic improvements in efficiencies in current generation and oxidizing power and can decrease internal resistance.

Broad Technical Challenges

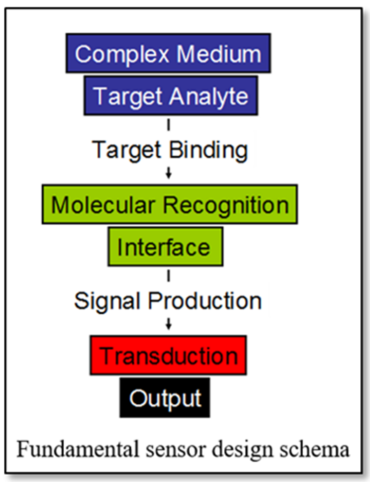
Identification and characterization of radionuclear- and chemically-induced biological responses can provide a useful method of detection where environmental fate and chemistries of nuclear materials yields an inconclusive signature, radiation levels are below mechanical limits of detection, or conventional physicochemical tracers are sample limited. In order to support advances in biological collection and detection, several conceptual challenges must be addressed. The general and pervasive themes associated with development of detection technologies, as well as those unique to biological systems, are discussed in greater detail below. Considerations include:

❖	Platform Integration
❖	Test, Evaluation, Validation, and Verification
❖	Considering Natural Environmental Versus Anthropogenic Sources in Measurement
❖	Radiation Detection
❖	Combined Chemotoxic and Radiotoxic Effects
❖	Chemical Detection

Table 2. Technical challenges associated with development of conventional and biologically-based monitoring systems

<u>Platform Integration</u>

In general, detection involves five primary steps: analyte binding or input, recognition, signal production, signal transduction, and output. However, variation of input parameters at each discrete step and the dynamic interfaces among steps contribute to a highly complex problem space.



Materials +	Transducers +	Transducer Geometry +	Modulation Parameters +	Parameter Shapes +	Multiple Modulation Parameters	Hyperspace of Chemical Sensor Features
10^8 *	10^1 *	10^2 *	10^2 *	10^2 *	10^6 =	10^{21} features

Figure 5. Above left, fundamental sensor design schema. Above center, theoretical dimensionality of the hyperspace of chemical sensor features.[73]

Stepwise design schema that fail to consider integration of system components at the inception of and throughout the developmental process are therefore unlikely to result in useful and/or reproducible technology. All such considerations apply equally to biologically-based or -enabled systems.

Exposure levels, whether from radiation or chemicals, must be sufficient to elicit a response which is also retrievable and quantifiable. As is the case for any detection scheme, availability of analyte is a primary issue. Although the present document does not explicitly discuss specific signatures or anticipated environmental levels of those signatures, it is acknowledged that development of useful detection motifs cannot be decoupled from such analyses.

Additional considerations apply where biological systems will be integrated into abiotic platforms. Living systems and components derived from them are frequently nonviable outside of the narrow range of conditions which define their native operations, thus more recent research efforts have sought to increase durability in a broader range of environments. General strategies include methods to ruggedize biosystems and/or provide the appropriate conditions to maintain viability outside the physiological conditions in which they conventionally reside. For platforms comprised of biological components (e.g., enzymes, peptides, DNA, aptamers, antibodies), trade-offs are reduced binding/catalytic efficiency, encapsulation that inhibits dynamic structural fluctuations needed for maximum efficiency, or surface crowding on solid support that may functionally reduce effective binding of analytes to active sites. For whole cell platforms (e.g., bacteria, archaea, fungi), tradeoffs may include slow diffusion of analyte through the cell encasement materials to the cell surface, reductions in cell viability due to harsh reaction conditions or over-proliferation of cells within confined spaces, and very low cell loading which may compromise sensor functionality and reproducibility.

Useful platforms will be predicated upon factors specific to the application space, such as specificity, storage needs, environmental stability, cost, and analyte(s) to be detected. Unique sets of end user requirements for such platforms will drive the selection of one system type over another.

Test, Evaluation, Validation, and Verification

Test, evaluation, validation, and verification (TEVV) of developed systems is important to ensure (1) quality of product and (2) compliance with design specifications and end user requirements. Interim assessments can and should be made in the laboratory setting, but, ideally, end-state products or components thereof should be independently assessed using standardized methodologies and testbeds. Important performance parameters are listed below in Table 1, although it is not an exhaustive listing.

Performance Parameter	Definition
Response time	Time required for sensor output to change from its previous state to a final settled value within a tolerance band (90 – 100%) of the correct new value
Linearity	Extent to which the actual measured curve of a sensor departs from the ideal curve
Coefficient of variation	Ratio of the standard deviation to the working range of the sensor
Limit of detection	Lowest value of a signature that can be detected
Limit of quantification	Lowest value of a signature that can be determined with an acceptable level of accuracy and precision
Repeatability (same day)	Precision under repeatability conditions within short intervals of time (2 – 4 hours)
Day-to-day repeatability	Precision under day-to-day repeatability conditions
Bias	Consistent deviation of the measured value from an accepted reference value
Robustness memory effect	Temporary or permanent dependence of readings on one or several previous values of the signature
Robustness interference	Undesired output signal cause by properties and/or substances other than the one(s) being measured
Dynamic Range	Ratio between the maximum and minimum signal acquired by the sensor

Table 3. Important performance parameters for detection platforms. Adapted from A common protocol for sensor testing – Report No.: 2011.001

Some of the molecular methods described in previous sections (e.g., biological markers) are not amenable to TEVV in the same sense as listed above, although the core principle of standardization still applies. Analytical validation is of critical importance to assess quality of technical procedures and data management as well as interpretation of results, particularly where new technologies or methods are applied. Both accuracy and precision of results are necessary to bolster confidence in the utility of novel monitoring approaches proposed herein.

Natural Environmental Versus Anthropogenic Sources in Measurement

Analyses involve integration of methods to measure subtle changes in organisms that are specific to the particular signature of interest and able to distinguish anthropogenic triggers from common environmental stressors and normal cellular processes. For example, challenges arise when energy production pathways generate endogenous reactive oxygen species (ROS) that are identical to cellular byproducts produced by the indirect effects of radiation, thus producing inconclusive results.[74,75] Analytical techniques must be able to differentiate between biochemical changes and cellular processes that are "normal", those that are induced as a consequence of exposure to "standard" environmental stressors, and those that are induced as a consequence of exposure to contamination associated with anthropogenic activity of interest, so that false positives and other sources of error can be eliminated.

Radiation Detection. The adverse effects of ionizing radiation (IR) on biological systems typically are classified as either deterministic or stochastic.[76] Deterministic effects are often associated with acute exposures, where deleterious changes are only elicited when the dose of radiation has exceeded a defined threshold that surpasses repair capacity. Such effects manifest in molecular and clinical outcomes which are detectable using well-established methods.

It is not clear, however, that deterministic effects are anticipated to predominate at exposure levels relevant to the present effort. Rather, stochastic effects which are associated with exposures to low and/or chronic doses of radiation may become the more important arbiters of biological change. Data from studies interrogating effects at the lower end of the exposure scale indicate that radiation may elicit non-DNA targeted effects, including bystander effects and genomic instability as well as other types of cellular and subcellular changes which are not predictable based upon linear extrapolation from high acute doses. For example, low dose radiation exposure results in a range of dose-response relationships for changes in the number, types, and patterns of gene expression. Low dose research using microbeams demonstrated that cells do not require a direct "hit" to result in significant biological alterations. These "bystander effects" demonstrate that "non-hit" cells respond with changes in gene expression, DNA repair, chromosome aberrations, mutations, and cell killing.[77] Bystander effect demonstrates the relationship between irradiated and non-irradiated cells[78] and exhibits heritable changes that include DNA damage, mutations, chromosomal aberrations, chromosomal instability, senescence, apoptosis, and oncogenic transformations.

Further, biological consequences may vary based upon the type and quality of radiation. For example, low-linear energy transfer (low-LET) radiation (i.e., γ- and X-rays) induces DNA double-strand breaks that are rapidly repaired. In contrast, DNA damage induced by the dense ionizing track of high-atomic number and energy (HZE) particles are slowly repaired or are irreparable.[79] High-LET radiation like alpha particles causes clustered damage along densely ionized tracks that instigate a high number of DNA lesions, including double strand breaks. The damage may challenge cellular repair systems and result in more profound as well as different levels and types of damage than that associated with sparsely ionizing radiation. X-, gamma-, and some beta-radiation exposures may elicit damage mostly through indirect mechanisms associated with radiolysis of cellular water which produces reactive oxygen and nitrogen species. Reactive species can damage multiple cellular structures, macromolecules, and organelles and can be regenerated for long periods following the initial irradiation event, leading to significant downstream effects. Direct and indirect damage is elicited by both high- and low- LET radiation, but patterns of damage could vary dependent upon the type, dose, and dose rate of radiation.

Type of Radiation	RBE
X-rays and gamma rays	1.0
Beta particles	1.0 - 1.7
Alpha particles	10 - 20
Thermal neutrons	2 – 5
Fast neutrons and protons to eye	32
Fast neutrons and protons	10
Heavy ions	20

Table 4. Relative Biological Effectiveness (RBE) is a relative measure of damage imposed by a given type of radiation per unit energy on biological tissues. Types and levels of damage can vary based on activity as well as dose.

The result of direct or indirect IR effects (including targeted and non-targeted effects) is the development of subcellular dysfunctions that manifest seconds to even decades later, thus certain changes are anticipated to persist for prolonged periods of time.[80] The consequences of radiation exposure on RNA, proteins, and small molecules that may exhibit susceptibility warrant further study using enabling technologies which have been specifically designed to study biological systems.[81–83] Evaluating direct as well as indirect effects associated with exposure to IR will enable identification of appropriate endpoints and, potentially, biological surrogates (i.e., proteins and other macromolecules) for use as recognition elements in nuclear sensing equipment. Further, developing a clear mechanistic understanding of responses predicated upon level and type of exposure will extend the utility of biological systems or components for environmental monitoring applications by providing isotope-specific information.

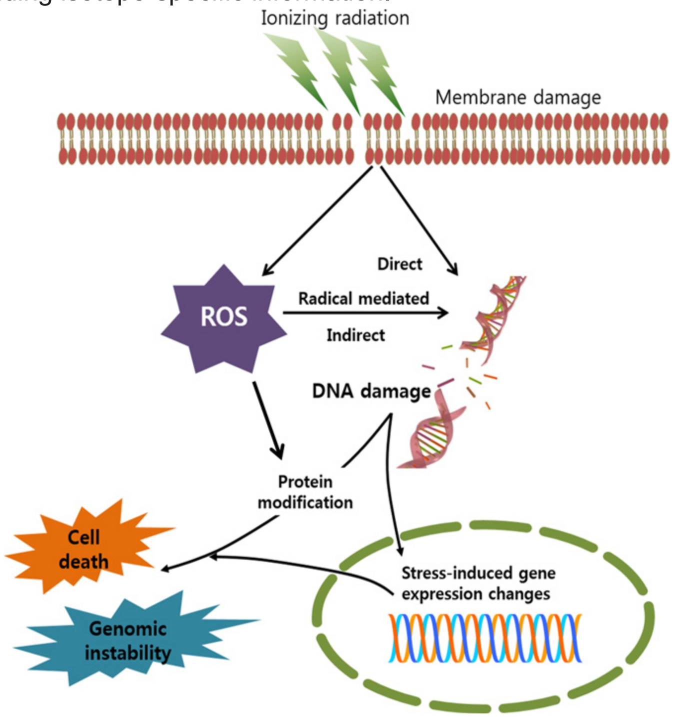


Figure 6. Cell responses to damage of DNA by ionizing radiation. Ionizing radiation causes single and double strand breaks of DNA, either directly or indirectly, resulting in oxidized proteins, DNA, lipids, and other biomolecules. Within minutes, the cell responds by altering gene expression and modifying stress-related proteins. High doses of radiation lead to cell death or genomic instability. Various degrees and types of radiation resistance along with interactions with radioactive chemicals offer a complex and integrated monitoring strategy[84]

Combined Chemotoxic and Radiotoxic Effects

Heavy metals are high-density elements that elicit toxic effects at relatively low concentrations. Radioisotopes of such metals are known to elicit chemotoxic responses equivalent to those elicited by the other isotopes because their chemical properties are essentially identical. However, radioisotopic compositions are known to additionally exhibit a wide spectrum of radiotoxic effects. Careful design of experiments to deconvolute biological changes related to chemotoxic versus radiotoxic effects will be important to understanding whether observed changes are the result of radioisotopes as opposed to heavy metal contamination that can occur as a consequence of multiple activities unrelated to nuclear processes.

Whereas uranium is arguably the most commonly studied radioisotope with respect to biological toxicity, very little information is available to assess the combined effects of the isotopes of other metals, such as Ag, As, Ba, Bi, Cd, Cs, Ge, In, Pd, inter alia. To further complicate matters, simultaneous exposures to multiple heavy metals can induce chemotoxicity that is additive, antagonistic, or synergistic. Studies to evaluate the joint toxicities of heavy metal mixtures will be necessary for elucidating biological responses and underlying mechanisms.85 Such approaches require analysis of responses at realistic concentrations of radioisotopes to build predictive value.

Chemical Detection

Numerous chemical signatures produced through nuclear activities serve as proxies for "smoking gun" evidence. Standard concerns, including limits of detection and reproducibility, analyte selectivity, and cross-reactivity, apply with respect to development of robust sensors. For environmental monitoring, an additional consideration is veracity of signature as it relates to characterizing the process of interest, as numerous industrial processes may result in similar effluents. Nuclear activities (including those associated with weapons development) can result in distinctive chemical signatures, such as enriched uranium, that are irrefutably tied to the process itself. Detection of highly definitive signatures can be complicated due to biogeochemical processes that change the nature of the signature prior to detection, natural attenuation that results in effectively non-detectable environmental concentrations, or deliberate recapture designed to thwart collection. However, chemical signatures may only be useful if seen in combination with established temporal and/or dosimetric information. Development of chemical detection systems that incorporate discrete detection elements into a single platform OR connect multiple platforms through networked detection may be necessary for identifying and characterizing chemical effluents that are also common to other industrial processes.

Development of arrayed detection schema introduce complications beyond those indicated in other sections and will require studies to establish structure/property relationships for higher order materials that potentially contain multiple types of binding moieties. Consideration should be given to sampling and separation systems, with special emphasis on design of surfaces to promote rapid and selective surface transport to appropriate sensor elements. Other considerations include evaluating "crosstalk" between biotic and abiotic sensor elements, developing on-board means for calibration and drift correction, designing algorithms for pattern classification and recognition, signal extraction, data fusion, and providing for spatial and temporal separation to improve signal to noise ratios.

Bionuclear Monitoring: Strengths, Weaknesses, Opportunities and Risks

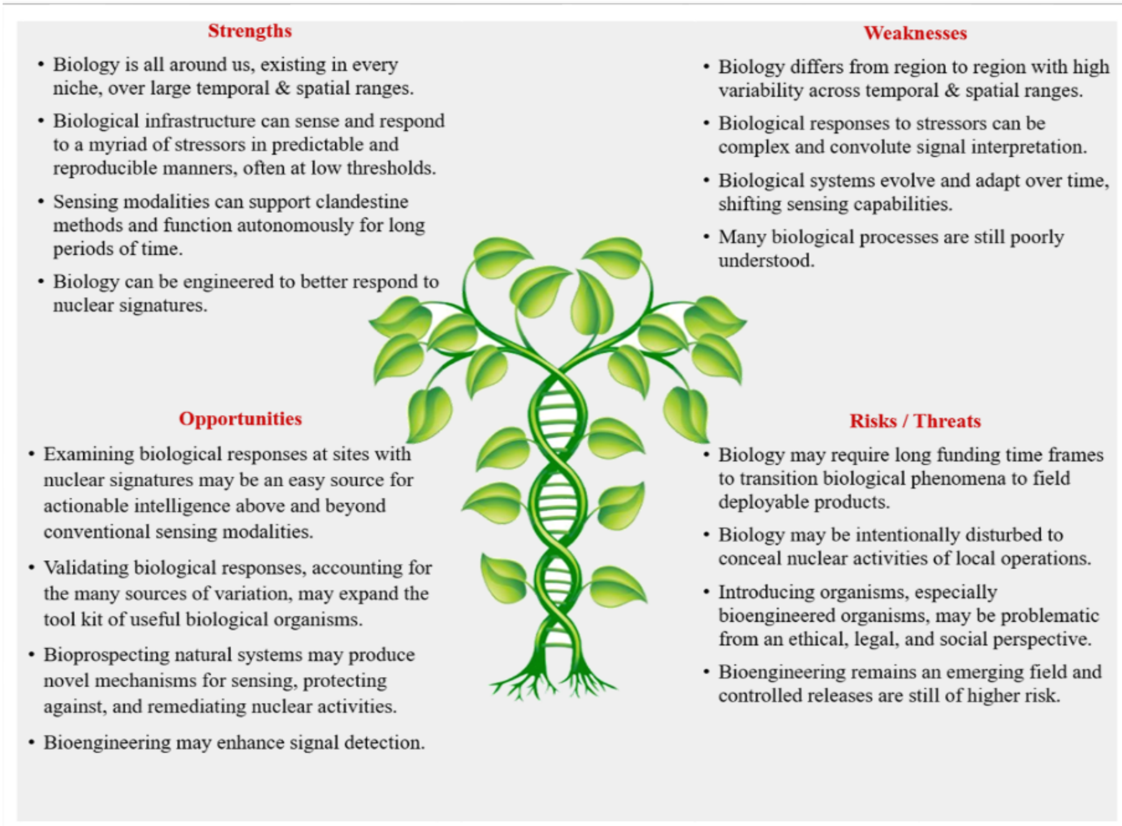


Figure 7. Biology offers many potential solutions for environmental monitoring, although consideration must also be given for associated challenges.

Conclusion

Bioinstructive materials, organisms, and systems are uniquely suited to address some of the shortfalls in extant C-WMD capabilities, and biologically-based technologies can provide an orthogonal means to enable completely new capabilities through development of disruptive technologies, or verify the veracity of existent information. Biologically-based and –enabled systems offer unprecedented selectivity for and sensitivity to a wide range of chemicals, heavy metals, and radioisotopes. Evolutionary processes make them particularly proficient at coping with environmental contaminants, either by adopting avoidance and mitigation strategies, or even, in some case, by incorporating those which are analogues to elements and compound commonly used in life-sustaining activities into metabolic processes and structures. Biosystems are routinely used to evaluate the health and well-being of at-risk ecosystems. It is logical to reason they will be an equally useful system for identifying facilities or processes that pose nuclear security threats because of their impacts on the surrounding biological and ecological systems.

Comprehensive developmental strategies will be required to achieve the envisioned ultimate goals. Near-term uses largely encompass building orthogonal or complementary collections, including biological materials (e.g., microbes, plants, animals) and environmental matrices that serve as repositories of biological material (e.g., soil, water, air). Early-stage research efforts should focus on adequate preservation and analysis of samples so that physiological, biochemical, and genetic information can be characterized in the relevant context, such as nuclear testing and facility processing. Mid- and long-term uses include integration of biological recognition elements into existing or future collection and detection platforms for improved sensitivity, specificity, remote sensing applicability. It is equally important to develop detection and monitoring biomarkers that can differentiate between transient and persistent presence of environmental changes, and that indicate the presence of certain environmental changes even when the stimuli are no longer present. Data integration and pattern recognition with machine learning and artificial intelligence, environmental biosignature characterization, and remote sensing strategy adaptation are essential underlying mechanisms.

The goals of work described herein are to i) exhaust all potential means of environmental monitoring in support of national nuclear security, ii) illuminate full use of the exponential increase in biotechnical means at our disposal to do so, and iii) provide tip-off or confirmatory technical evidence of capabilities to counter WMD activity to both tactical and strategic decision makers. In three subsequent technical articles, we will provide comprehensive analysis and more examples of past and current work that is representative of the aforementioned overarching groups. Select CONOPS may emerge as more likely or tenable than others, and those concepts will be highlighted. In addition, scientific or technical limitations to critical gaps will be further discussed. The end-state objectives are to provide a logical framework for assessing current biologically-based and –enabled capabilities and to facilitate identification and development of promising technologies intended for use in environmental monitoring scenarios.

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Augmenting field nuclear forensics capabilities with handheld atomic spectroscopy devices for nuclear debris analysis

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The realm of technical nuclear forensics remains a critical part of joint counterproliferation capabilities. Since the passage of the Nuclear Forensics and Attribution Act (H.R.730) in 2010 [1], the nuclear science community has undertaken steps to bolster national nuclear forensics capabilities under the National Technical Nuclear Forensics Center. Within the technical nuclear forensics umbrella, one particular area of interest involves developing capabilities for in-field analysis of nuclear material. This includes engaging in field training exercises across relevant branches of the military and investigating new technologies to conduct field nuclear forensic analyses. The integration of novel analytical technologies into real-world nuclear detection scenarios is crucial for the development of improved nuclear forensic analytical methods and strategies across the US military. Furthermore, partnerships between Department of Defense (DOD) and Department of Energy (DOE) components in these endeavors allow for the leveraging of greater resources and knowledge for testing and evaluating new technologies and methods for nuclear forensic analysis.

In October 2021, a team from the Air Force Institute of Technology (AFIT) joined members of the 20th CBRNE Command for a field exercise at the Nevada National Security Site (NNSS). Two commercially produced handheld geochemical analyzers were implemented for in-field analysis of nuclear debris for the very first time. Previous research with these devices to evaluate and develop their initial technical nuclear forensics capabilities did not extend beyond the laboratory setting. This exercise proved the utility of the portable spectroscopic analyzers for geochemical analysis of nuclear debris,

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allowing the field team to rapidly identify elements of interest in debris samples across several test sites. This investigation into the field capabilities of commercial, off-the-shelf (COTS) elemental analyzers highlighted the potential these devices have for use in joint technical forensics endeavors. Overall, this endeavor demonstrated an initial evaluation of a new technical forensics capability in the military operational environment, in spite of challenges posed by COVID-19. Providing relevant US military components with a new, more portable field confirmatory measure to ascertain elemental characteristics of nuclear debris material would greatly bolster US military technical nuclear forensics capabilities.

Portable Element Analyzers

Figure 1. SciAps Z300 LIBS analyzer (left) and Bruker S1 Titan XRF analyzer[2,3]

Portable atomic spectroscopy analyzers have become commonplace tools in various industries, such as metal scrapping and geology [2,4,5]. These compact, lightweight analyzers can easily be used in the field for rapid determination of the elements in each sample, to include relative abundance of said constituent elements. The versatility, size, and relatively low cost of these tools has made them a prime candidate for experimental investigations in the nuclear science field to evaluate their potential as tools for nuclear material analysis. Two such analyzers are shown in Fig. 1 above. The SciAps Z300 is a portable laser-induced breakdown spectroscopy (LIBS) device [2]; it uses a 5-mJ/pulse Nd:YAG laser to ablate the surface of a sample. Electronic de-excitations from the ablation are recorded by the onboard spectrometer system, and a spectrum of the emitted wavelengths is recorded. The on-board software then performs chemometric calculations to determine the chemical makeup of the sample and the relative elemental abundances from the recorded spectra. The Bruker S1 Titan in Fig. 1 (right) is a portable x-ray fluorescence (XRF) analyzer [3]. This device generates x-rays across a range of energies directed at the target sample to eject inner shell electrons. As outer shell electrons move to fill these vacancies, a fluorescence x-ray is emitted. These fluorescence emissions are collimated and recorded by a detector to generate an XRF spectrum, which can be similarly used to determine the constituent elements of a sample and their relative concentrations.

Several studies have been conducted over the last few years using portable LIBS devices for nuclear material analysis within a laboratory setting. An early study conducted in 2010 by Barefield et. al. introduced a backpack, field deployable LIBS setup for detecting uranium contamination on various metal surfaces [6]. This initial study proved possible utility of portable LIBS systems for nuclear material detection and international safeguards applications. Manard et. al. applied a SciAps Z500 LIBS device in 2018 for the characterization of rare earth metals in uranium matrices, providing confirmation that the newer handheld device could not only identify spectral signatures of uranium, but discriminate small amounts of other heavy metals in the nuclear material [7]. Similarly in 2017, Shattan et. al. implemented the same handheld LIBS device for detecting uranyl fluoride (UO2F2) surface contamination, achieving a detection limit of 250 parts-per-million [8]. While these laboratory studies indicate that portable LIBS systems (or similar handheld atomic analyzers) could provide a beneficial augmentation to the field detection and quantification of nuclear material, such devices have not been thoroughly tested in an operational environment. The work done by our team at AFIT represents the first field testing of such devices for analysis of nuclear material, to evaluate their potential as rapid confirmatory tools for quantitative chemical analysis of nuclear bomb debris.

Field Analysis Methodology

The handheld analyzers provide spot measurements of selected samples and are unsuitable for surveying a large debris area. However, they do integrate well into current technical forensic methods when paired with other technologies used to survey large field areas for nuclear material. In this exercise, six different historical test sites at the NNSS were chosen for surveying. Relevant site data, including debris type, device yield, height of burst (HOB) and number of samples recorded are listed in Table 2.

Site number	Debris type	Yield	HOB	Samples taken
1	Particle	500 t	-1 m	11
2	Deposition	500	-30 m	10
3	Particle	22 t	+1 m	9
4	Deposition	30 kt	+1 m	8
5	Particle	18 t	-110 m	10
6	Particle/Deposition	44 kt	+210 m	18

Table 2. Description of sites surveyed and associated test device parameters[9].

The collection team with the elemental analyzers worked with several collection teams comprised of Soldiers from the 20th CBRNE, shown in Fig. 2, surveying each site with ThermoFischer RadEye personal radiation detectors. These detectors respond to the presence of beta and gamma radiation in the environment. The handheld analyzer team followed the ground teams through the survey area as they found and collected nuclear debris. Two distinct types of debris were found and analyzed with both LIBS and XRF. The bead-like nuclear debris, identifiable by its vitreous luster and colloidal fractures, forms from aerodynamic particulates cooling while descending through the atmosphere to the ground after detonation. Example of collected debris pieces are shown in Fig. 3.

Figure 2. Ground collection team at test site.

Figure 3. Aerodynamic nuclear debris pieces from test.

The second debris morphology appeared as particulate deposition on larger rock surfaces scattered around the bomb craters. This debris exhibited similar vitreous luster and coated portions of the surfaces of the larger rocks in the vicinity of the crater rim; an example is shown in Fig. 4.

Figure 4. AFIT collection team (MAJ Sutphin, 1st Lt Rao, LTC Dugan) surveying deposition debris around a bomb crater.

When debris was detected by one of the survey teams, the following methodology was used to record LIBS and XRF spectra from selected samples. The LIBS device was used with a gate delay of 250 ns and a repetition rate of 10 Hz to scan an 8x8 raster pattern across the surface of a sample or deposition area. This effectively took 64 spectral recordings within a localized area of the sample and average them into one representative spectrum. An XRF recording was taken on each sample as well, using a multi-phase recording with a 15-50 kV voltage sweep lasting 120 seconds to generate one XRF spectrum. This methodology enabled the quick collection of several spectra from different samples across each test site. Fielding the handheld analyzers for use with a simulated ground collection team proved to be easy and effective. The compact size of these devices makes them ideal for field forensics use in an operational environment, such as the desert terrain of the test sites. From a strategic standpoint, the potential for augmenting the toolkit of ground collection teams with an easy to use, rapid result, field confirmatory device for nuclear debris analysis cannot be underscored enough. Such a capability would enable military forensics teams to see nearly instantaneous results about the chemical composition of a target sample in the field. This would greatly improve the quality of data taken during such field exercises and collection operations, as the ground teams would be able to record spectral signatures indicating the presence of short-lived elements which could decay by the time the sample is transferred to a traditional lab for analysis. The results of this exercise definitively confirm that these handheld atomic analyzers can be easily integrated into a ground collection team to gain additional information and important signatures about nuclear debris in the field.

Analysis of Recorded Spectra

Following the data collection events at each test site, the spectra recorded with both the devices were post-processed for further analysis. The elemental makeup of nuclear debris reflects the natural components of the test site environment and anthropogenic material from the actual device. Example LIBS and XRF spectra of a debris piece is shown in Fig. 5.

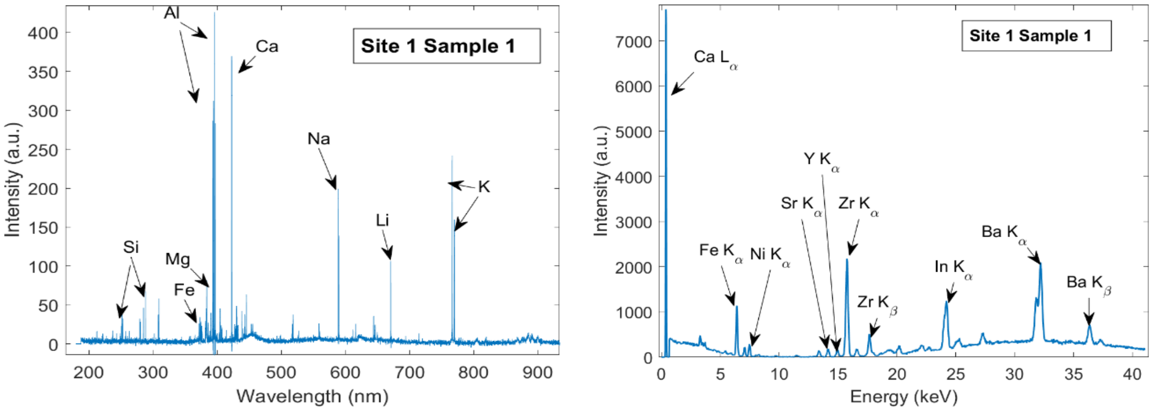

Figure 5. LIBS (left) and XRF (right) spectra from the same debris sample with major emission peaks marked.

The major emission lines are labeled according to the element associated with the atomic transition; the bulk geochemical makeup of these samples is characterized by oxide compounds of the various metals labeled in the spectrum. Aluminum, calcium, sodium and potassium oxide compounds are the most prevalent in these debris samples. These results parallel previous analyses of the makeup of trinitite, which is composed mainly of SiO2, Al2O3, CaO, K2O, and FeO [10]. The exact abundances of these bulk oxides vary depending on the presence of precursor minerals in the sand at each test site. Nevertheless, emission signatures corresponding to all of these bulk oxides are easily identified in the two spectra. Additionally, the trinitite analysis took place in the laboratory setting using an inductively couple plasma mass spectrometry (ICP-MS) technique. Being able to replicate laboratory analysis results on nuclear debris with handheld devices in the field is a huge leap forward in technical forensics capability, as these devices gave nearly the same information about the bulk constituents of the debris within seconds.

It is important to distinguish the exact results of the spectral recordings between the two devices. The LIBS devices is marketed as a geological tool, and thus was able to easily record major emission lines of the bulk mineral oxides in the debris (Si, Mg, Fe, Al, Ca, Na, K). While the XRF also has the capacity to conduct robust geological analysis, it is difficult for handheld devices to induce fluorescence in lighter elements. The Bruker S1 Titan used in this field exercise cannot detect elements with $Z<12$ (Na and below). Elements with $Z<14$ (Si) are often difficult to identify as their K-shell emissions are in the 0.1-2 keV range and cannot be easily resolved from the background noise continuum. However, the XRF does appear to identify minor constituent elements in the debris samples better than the LIBS device; the plethora of LIBS emissions can make it difficult to find minor or trace element emissions free of spectral interferences. The XRF spectrum in Fig. 5 identifies non-mineral constituents such as Ni, Sr, Y, Zr, and Ba; all of these elements have been quantified in trace amounts (10-1000 ppm) in trinitite by LA-ICP-MS. While all these elements could be present in soil minerals in the test environment, Ni and Ba can also indicate anthropogenic activities. Ni is often present in alloys used for the test devices or other hardware, and many older nuclear devices used Baratol (Ba(NO3)2/TNT) in the explosive lenses. Detecting indications of device materials or explosive residue in the field can help direct the nuclear forensics investigation and yield important information about device makeup. Additionally, the Sr peak can also indicate the presence of Sr-90 in the debris, a fission product derived from Rb-90 [11]. While the presence of the particular Sr-90 isotope would have to be confirmed in a laboratory, the handheld devices can help a field forensic analyst evaluate the possibility of nuclear reaction products in the debris before the samples are shipped off-site.

A further analysis of minor emissions in the spectra can help yield information about other trace elements of interest, or perhaps even possible sources of radiation in each debris sample. Fig. 6 displays several overlayed sample spectra from Site 1; many of them contain a minor emission triplet of Cs (259.9 nm, 261.1 nm and 263.2 nm). Cs-137 is a well-known fission product formed from the beta decay of Xe-137 and I-137; it is commonly found in samples from the Trinity test site even though more than six decades have passed since the test [11]. With a half-life of 30 years, one would expect this isotope to still be present in the debris at many of the test sites at NNSS. An in-field gamma spectrometry recording would have to be conducted in tandem to verify the isotopic identification of Cs-137 by looking for the 661.6 keV gamma ray, as a stable isotope Cs-133 does exist. However, Cs-133 is mainly found in the rare mineral pollucite which would not be present in significant quantities at the Nevada test site, therefore the LIBS measurement gives a good initial indication of the presence of Cs-137. This is a significant result, as it provides an early proof of concept showcasing how this commercial LIBS device can be used in nuclear forensic analysis and detect elements of interest to the nuclear fuel cycle. When fielded with a portable gamma spectrometer, the two devices together could enable a ground collection team to conduct rapid geochemical analysis of nuclear debris in the field and confirm the presence of distinct radioisotopes to characterize the nature of the debris and the nuclear reactions that occurred at the survey site.

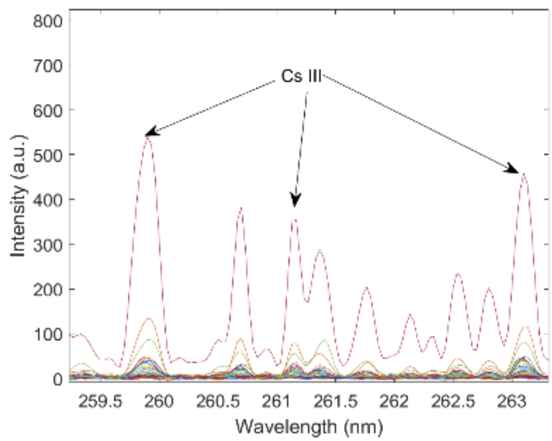

Figure 6. Portion of Site 1 LIBS spectra with labeled Cs atomic emission lines

Examining the 3 – 6 keV band of the Site 1 average XRF spectrum, shown in Fig. 7, reveals smaller emissions of the bulk constituents Ca and K as well as minor constituents Mn and Ti. The most significant finding in this data is the presence of the 2.95 keV Ra M-shell peak.

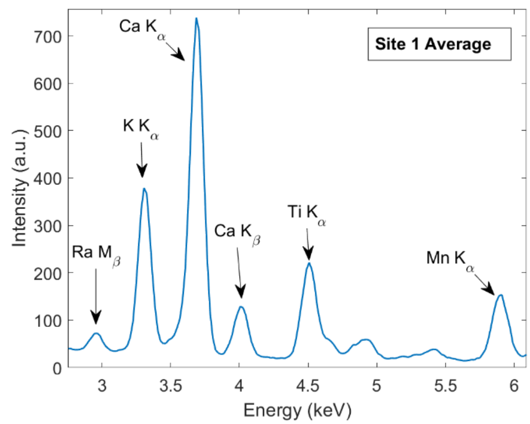

Figure 7. Minor XRF emissions in Site 1 average spectrum

All isotopes of Ra are radioactive and are only present naturally at part-per-trillion levels in the Earth. Ra-226 is a direct decay product of U-238 with a half-life of 1600 years, and the presence of the Mβ peak at a noticeable intensity indicates that the debris samples at this site are likely to contain traces of this isotope originating from the nuclear test device itself. The results of this inspection indicate that the handheld XRF also has the potential to gather signatures of important trace elements, potentially even radionuclides, from debris in the field in the span of minutes. Additionally, the spectra recorded by this device are much easier to read and visually analyze; a ground team member with no spectroscopy background could very well take a cursory glance at a recording taken in the field and quickly discern signatures of interest from the data. While the complete analysis of this data set and the spectra from all six surveyed sites is still in progress, this initial investigation into the results from the first test site shows promising indications of the nuclear forensic analysis capabilities of these two handheld devices. These commercial analyzers are neither designed nor marketed for analysis of nuclear material, yet they have been demonstrably proven to have this capability. Both analyzers were easily and rapidly able to discern information about not only the bulk chemical makeup of nuclear debris samples, but they were also able to record important emission signatures of minor elements corresponding to device materials. Additionally, both devices yielded emission signatures of potential radionuclides in the debris indicating the occurrence of nuclear fission events and presence of nuclear fuel material. Even though the limited resolution of these devices prevents direct identification of isotopes, they can rapidly identify emissions belonging to elements of interest whose radioisotopes could be present in the debris. Paired with beta or gamma spectroscopy equipment, these devices could not only serve as a field confirmatory capability for identifying nuclear debris, but also rapidly identify and record key material signatures of debris which may not be present when the samples are shipped off site to the laboratory. This would significantly bolster the data available for nuclear forensic analysis and attribution and allow the technical forensics process of discerning the nature of the debris to being in the field itself.

Conclusion

Evolving commercial technologies present great opportunities for new capabilities to be introduced in the realm of technical nuclear forensics. Adapting existing commercially produced analytical equipment for field use and testing the capabilities of such devices is necessary to advance joint counterproliferation abilities and retain technological dominance for continued mission success. This recent evaluation of the use of handheld elemental analyzers for field nuclear forensic analysis represents a step forward in ensuring enduring counterproliferation capabilities and technological evolution. The handheld LIBS and XRF analyzers implemented in this field study clearly performed beyond their original design capabilities and provided a ground survey team with the ability to rapidly characterize nuclear debris and discern important nuclear forensic signatures nearly instantaneously. Both devices were integrated seamlessly into the ground survey exercise, despite this being the first real field test of the handheld analyzers for nuclear debris analysis. If fielded along with portable radiation detectors, such as beta or gamma spectroscopy analyzers, these devices could yield a rapid, field confirmatory capability to ascertain information about not only the bulk chemical makeup of nuclear debris but also specific radioisotope signatures which could decay during sample transport to an off-site laboratory. The initial results of this exercise indicate that handheld elemental analyzers have the potential to provide a significant beneficial augmentation to the current field technical forensics toolkit used by US military components. Further field testing of these technologies could greatly bolster future nonproliferation capabilities and enhance US efforts to maintain a dominant technical forensics posture.

Notes

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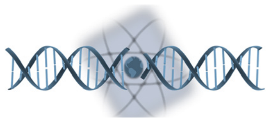
Harnessing the Environment to Identify Nuclear Processes:

I. Biological Markers to Assess Environmental Exposure



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Abstract

The present article serves as a companion piece for "Harnessing the Environment to Identify Nuclear Processes", also published in the 24th edition of the CWMD Journal. There, we presented an overview on the use of natural or engineered biologically-based systems as radiation, biological, and chemical indicators for detection and analysis of nuclear proliferation activities not readily discernible by current methods of monitoring. Biological systems can be leveraged to augment or replace current methods of surveillance through the use of indigenous flora and fauna or those engineered to render specified capabilities. Such systems not only collect but often concentrate materials of interest, thus allowing detection of trace amounts and retention of signal that may otherwise be lost to standard sampling, and, through exploitation of biological signatures, provide a log of activity which allows reconstruction of ephemeral and short-lived events that often challenge conventional monitoring techniques. The approaches described herein focus on the use of naturally-occurring microbial species, multicellular organisms and biologically-derived materials, and ecological networks for collection and analysis or, in some cases, for remote interrogation. Although several of the constructs can be adapted for immediate use, others will require additional research to develop fully mature capabilities for incorporation into the nuclear monitoring toolkit.

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Introduction

The present article serves as a companion piece for "Harnessing the Environment to Identify Nuclear Processes", also published in the 24th edition of the CWMD Journal. There, we presented an overview on the use of natural or engineered biologically-based systems as radiation, biological, and chemical indicators for detection and analysis of nuclear proliferation activities not readily discernible by current methods of monitoring. Current approaches for certain concepts of operation are limited in scope by logistics and instrumentation, and few, if any, near- to mid-field detection schema that meet requirements for covert and persistent environmental monitoring presently exist. We posit that recent advances in the life and physical sciences allow for exploitation and optimization of biological systems to serve as indicators of illicit nuclear activity.

Biological systems can be leveraged to augment or replace current methods of surveillance through the use of indigenous flora and fauna or those engineered to render specified capabilities. Such systems not only collect but often concentrate materials of interest, thus allowing detection of trace amounts and retention of signal that may otherwise be lost to standard sampling, and, through exploitation of biological signatures, provide a log of activity which allows reconstruction of ephemeral and short-lived events that often challenge conventional monitoring techniques. Natural systems require no power, specialized equipment, or complicated emplacement strategies. In cases where organisms do not possess the intrinsic capability to concentrate and/or signal the presence of specific agents, components and pathways within naturally-occurring systems may be engineered to develop the necessary capacity while still operating in accordance with the performance parameters generally described above.

To date, however, limited effort has been applied to investigating the utility of living systems or discrete components and pathways derived from them to assist the development of novel monitoring strategies specific to the identification and characterization of nuclear processes. Most efforts related to environmental monitoring are relevant to either bioremediation (e.g., phytoremediation of contaminated sites) or evaluate endpoints that are not directly useful for the purposes described herein. Recent advances in the fields of biophysics, analytical chemistry, and computational modeling *inter alia* provide unprecedented ability to interrogate and manipulate single-celled as well as multicellular organisms at system and sub-system levels, therefore lending credence to the notion that biological collection and sensing motifs can be successfully developed. The approaches described herein focus on the use of naturally-occurring microbial species, multicellular organisms and biologically-derived materials, and ecological networks for collection and analysis or, in some cases, for remote interrogation. Later articles will explore other applications of biological systems and the enabling technologies that support their use.

Microbial Species

Microorganisms exist in every natural biome, with extremely high population densities per gram of soil, or milliliter of air or water (Figure 1).[1] The term microorganism has broad reach and includes bacteria and archaea, algae, protozoans, fungi, and lichens (symbiosis between fungi and algae). While microbiome communities exist in concert with various higher organisms such as animals and plants, this article focuses on those specific to general environmental settings such as soil, water, and extreme conditions. Most living organisms, including microbes, respond to environmental stimuli such as exposure to ionizing radiation (IR) and chemical compounds. Distinct types, or levels, of radiation result in degrees of physiological, biochemical, and/or genetic outcomes which may be either broad or specific to different microbes.[2] These outcomes can manifest in changes to population density and diversity and alteration of physiological, genetic, or proteomic responses. The tremendous abundance and diversity of microorganisms, and their responses to environmental inputs provides unique opportunities to use them as monitors of the environment, and potentially provide signatures, for example, of nuclear activity.

While microorganisms are traditionally studied individually, a vast majority of environmental microbes are not cultivable or isolatable with current techniques. A new scientific discipline has been established and advanced in recent decades to investigate features and functions of microbes

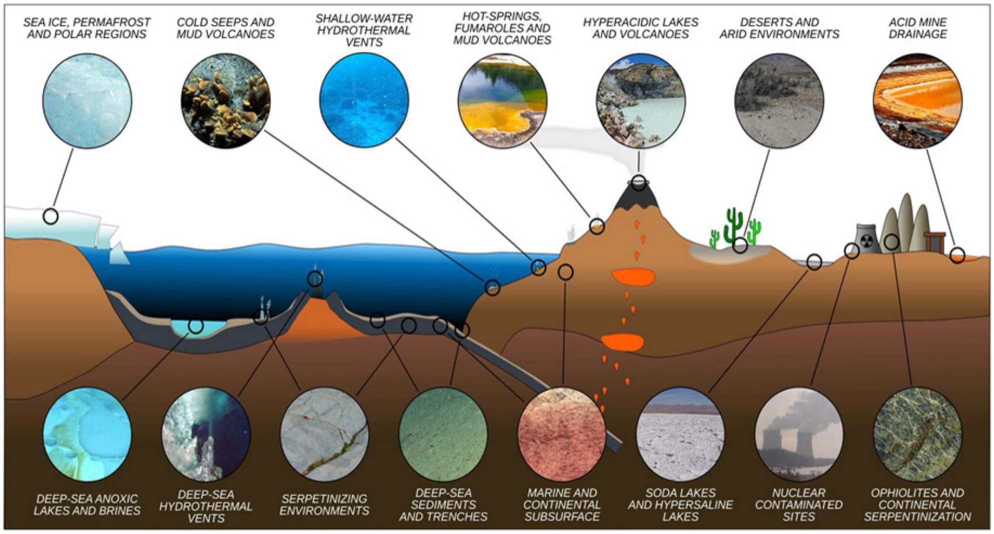

Figure 1. Illustration of the myriad of environmental niches where microbes have been identified. (Taken from Merino et al. 2019)[1]

as a community in their indigenous environment. *Microbiome* is a collective term that describes membership of all the microorganisms living in a loosely defined community. These complex communities often rely on the specific physiological interactions of different species to provide carbon and energy sources for other microbial members. The availability and concentrations of these chemicals play a significant role in determining the dominant type(s) of microbial activity at any given location.

The ubiquity and vast abundance of microbes in the environment, and their responses to environmental stimuli and conditions offer advantages as monitors for radiation exposure. Microbes evolve to adapt to their environment and react to long- and short-term environmental changes which are manifested as changes in the composition of the microbial community and/or changes in the genetic makeup of the microorganisms that comprise the community. Nuclear incidents and controlled irradiation experiments on bacterial isolates have shown genetic and metabolic changes in microorganisms in response to radiation. These changes can be transient or persistent.

Most microbial populations reside in environments that are considered suitable for living organisms. However, optimum growth conditions for certain species could occur at extreme temperatures (near freezing or near or above boiling), very acidic or extremely alkaline, low to high salt concentrations (osmotic stress) and degrees of oxidation/reduction (redox) conditions (Table 1). By regarding microbial populations as data-rich environmental sensors and response elements, monitoring scenarios can include sample collections, in-situ sensors, and/or remote sensing. Further, the ability to incorporate microbes into synthetic biology and bioengineering enables the potential for their use as reporters as well.

Factor	Range
Temperature	< 0° to 100° Celcius
Osmotic Pressure	< 1% to 35%
pH	~1 to 10
Water Availability	≥ 60%
Redox Conditions	~400 to 800 millivolts

Table 1. Microbial growth ranges.

IR exposure to a microbial population can be detected as:

- Overall changes in the microbial density and diversity in an area, both chronic and acute
- Physical alterations in the cells, including contaminant sorption, cellular injury/stress
- Changes to metabolic activity (i.e., CO2 release, oxygen or nitrate use, etc.)
- Modification of genetic responses due to radiation.

Microbes can be isolated from the environment through physical removal of small sample sizes of a few milliliters or grams. Filtration from water or air can separate cells based on size through various filter pore sizes. Cell desorption from soil particles can also be accomplished[3] and could lead to filtration and further analysis. Once concentrated, cells can be analyzed for overall changes of taxonomic and functional diversity through molecular techniques that categorize a microbial population based on genus or species, physiological characteristics and even changes in specific genes. The term operational taxonomic unit (OTU) is often used in molecular biology to represent a genus- or species-level relationship.

Molecular techniques are useful in understanding the genetic structure of a species (genomics) or the genomes of a mixed community (metagenomics). Additionally, transcriptomics relates to specific metabolic function at any given time. Proteomics refers to existing proteins and changes due to environmental conditions. Metabolomics is the study of chemical fingerprints that specific cellular processes establish during their activity.[4]

Nuclear materials, and chemicals associated with nuclear activity (e.g., fluorides, nitrates, halogenated organic compounds), can elicit immediate state changes in microbial communities.[2,5-7] Profiling these state changes via nucleotide sequencing of evolutionarily conserved gene sequences or whole genomes, allowing identification of microbial sentinels.[8,9] Popular targets include the 16S rRNA gene for bacteria and archaea, 18s rRNA gene for fungi, inter-transgenic spacers for bacteria, archaea, and fungi, and whole community metagenomics for all. Fluorescent antibodies specific to particular cellular components, and fluorescent probes linked to specific genes are well established methods of analyzing environmental samples. These techniques are often enhanced with flow cytometry[10] and electrochemical techniques as a means of rapid and quantitative detection. In addition to profiling community membership, researchers are looking into functional components of microbiomes. Measurements of small molecules, metabolites, proteins, and gene transcripts aside from, and in conjunction with, membership profiling may provide optimal monitoring solutions.

While this is not meant to be an exhaustive review, the following sections introduce what is known about environmental microbial communities related to common nuclear and radiation sources and exposure levels. Highlighted are gaps in current knowledge and potential utility of microbiota in detection, sensing, and reporting of nuclear sources and sites.

<u>Soil Microbiomes.</u> Microbial communities within soil can be very diverse in composition and geographical sites, depending on whether or not members are motile.[11] This creates an interesting situation whereby organisms can be used as snapshots of single events or changes over time. Studies profiling microbial response to and influence on the local environment are highlighted below.

At the Department of Energy's Oak Ridge site containing uranium (U) contaminated soil, a controlled input of ethanol as an electron donor was introduced to stimulate the resident microbial community to facilitate U(VI) reduction. This prompts immobilization of U and aids in remediation of the soil. When compared to non-treated sites, the ethanol-treated sites had several enriched bacterial genera suspected of performing this unique bioremediation activity.11 Among these enriched genera, *Desulfovibrio* species (spp.) and *Anaeromyxobacter* spp. are known U(VI)-reducers, with the latter previously associated with contaminated subsurface environments. *Rhodopseudomonas* spp. were also enriched and, while not much is known of representative species to reduce metals, the completed genome of *Rhodopseudomonas palustris* revealed the presence of several cytochrome C genes (involved in bioremediation processes), thereby suggesting that other members of this genus possess similar capabilities. Enrichment of unspecified *Pseudomonas* spp. signatures suggests that some species could metabolize aromatic or chlorinated compounds. In parallel, the researchers investigated the functional responses through the identification of expressed gene signatures to elucidate the potential microbial activities related to U reduction. Using the GeoChip microarray, capable of identifying 2,300 genes, benzoyl-CoA reductase (catalyzes ATP-driven aromatic ring reduction), sulfate reduction, and dissimilatory bisulfite reductase were the predominantly expressed genes found in the treated U sites.[11]

Cesium-137 (Cs-137) remains as the primary source of gamma radiation in the soils surrounding the Chernobyl disaster site[12], where networks of large trenches were constructed to collect the radionuclide waste. Of these, trench 22 (T22) has been used to understand the transfer of radionuclides to the environment. In this study, investigators utilized next-generation sequencing (NGS) platforms to capture as much of the bacterial and archaeal diversity from both the trench site and the surrounding soils. Among the bacterial signatures were *Acidobacteria*, AD3, *Chloroflexi, Proteobacteria, Verrucomicrobia,* and WPS-2. Of the archaeal signatures, Crenarchaeota were dominant. Of interest is that there were no cultured bacterial representatives from the trench site, except for *Bradyrhyzobium, Rhodoplanes, Burkholderia,* and *Sinobacteraceae*. These results highlight the benefit of both culture-based and independent techniques, alone and in concert, for profiling complex communities.

In a related study, microbiota were measured and compared at the Chernobyl and Fukushima disaster sites as signatures of Cs-137 and Strontium-90 (Sr-90) exposure.[13] Interestingly, soils in the nearby region of reduced radionuclide contamination had greater bacterial diversity. Microbial sequencing efforts between these two sites revealed 417 shared OTUs, among them being members of *Rhodospirillales, Acetobacteraceae* and C*andidatus Solibacter, Acidimicrobiales, Verrucomicrobia, Bryobacter, Rhizobiales, Proteobacteria*, subgroups 1 and 2 of A*cidobacteria, Ktenodobacterales, Chloroflexi,* and *Thermotogales*, with the most abundant OTUs representing the *phyla Actinobacteria, Acidobacteria*, and *Proteobacteria*. This same study reported certain genes of specific bacteria that could be associated with exposure of specific radionuclides. Some genes and bacteria associated with Sr-90 were IS110 family transposase (T*erriglobus saanensis)*, *amidohydrolase and tetratricopeptide* TPR_1 repeat-containing protein (both from *Gemmatirosa kalamazoonesis*), putative *peptidase* S8 and S53 *subtilisin kexin sedolisin* (*Tetrasphaera japonica* T1-X7), response regulator (*Acidobacteriaceae* sp. KBS89), ABC transporter permease and serine/threonine protein Kinase (both from *Candidatus Koribacter versatilis*), PAS domain S-box protein (*Singulisphaera acidiphila*), among several others. For Cs-137, suspected associated bacterial genes were magnesium-translocating P-type ATPase (*Bryobacter aggregatus*), SAM-dependent methyltransferase (*Candidatus Solibacter usitatus*), peptidase M14 carboxypeptidase A (*Gemmatirosa kalamazoonesis*), and 2-oxoglutarate dehydrogenase E1 component (*Acidobacterium ailaaui*), among others. For both Sr-90 and Cs-137, associated bacterial genes were multidrug efflux RND transporter permease subunit (*Candidatus Koribacter versatilis*), tonB-dependent receptor (*Granulicella tundricola*), and GntR family transcriptional regulator and tetratricopeptide repeat protein (both from *Acidobacteriaceae bacterium* KBS 83), among others.[13] While the influence of radiation on gene expression or the influence of gene expression on radiation response was not characterized, they still provide meaningful targets for developing profiles related to each source.

Methylated iodine-129 (I-129) represents a threat to public health as long-term exposure results in its accumulation in the thyroid. One study sought to explain the biogenic methylation of I-129 released from nuclear facilities and dispersed into the atmosphere and water systems, because global methylated I-129 (up to 4×10^{11} grams per year (g/yr)) could not be explained solely from microalgae activity (up to 10^{10} g/yr).[14] Through microcosm-based cultivation studies with gas chromatography, the researchers were successful in demonstrating and quantifying known soil microbes' methylation of I-129: *Methylobacterium* sp. strain MRCD 18, *Pseudomonas straminae* JCM 2783, *Rhizobium* sp. strain MRCD 19, *Rhodococcus equi* JCM 1311, *Variovorax* sp. strain MRCD 30, and *Zoogloea* sp. strain MRCD 32.[14]

Aquatic Microbiomes. Marine and freshwater environments harbor bacterial communities that, like those of diverse soil systems, contribute to the cycling of nutrients and compounds available to specialized microbial subsets that can metabolically leverage these potential energy sources. Identifying microbial signatures in response to perturbations, such as from radiation, metals, or organic compounds, permits an understanding of biological responses to abiotic influences.

Uranium tailings are usually contained within liners, sealed, and covered in soil after decommissioning. Owing to uranium's toxicity and high solubility in the environment, implications regarding groundwater contamination are a major concern. In the case of the Deilmann Tailings Management Facility, waste tailings are contained in a deposition site covered in nearly 40 m of water to prevent particles from being aerosolized and shield escaping radiation.[15] To profile viable bacteria previously isolated from this site, researchers devised an *in situ* cultivation strategy utilizing polycarbonate coupons submerged at 13 m intervals of depth, up to 41 m. When recovered, replicates of these coupons have shown the presence of biofilms after three months of cultivation. Inductively Coupled Plasma – Mass Spectrometry analysis showed no trends in specific metal accumulation, although dissolved concentrations of vanadium and molybdenum appeared to increase with greater depth, while dissolved concentrations of manganese decreased. Cultivation of viable cells highlighted certain bacterial genera associated with depth and available carbon sources: *Polaromonas* appeared to increase in abundance with greater depth, while *Methylobacterium, Dechloromonas*, and *Aquabacterium* decreased with greater depth. Both *Polaromonas* and *Acidovorax* were found at the 41 m depth, while *Ralstonia*, (some species of this genus are known to reduce iron (Fe)), was found across all depths.[15]

Spent nuclear fuel (SNF) rods are stored in bins with water to help dissipate heat and radioactivity during their decay. Typically, the aluminum coatings on the SNF are well suited to prevent corrosion during this long term storage. However, white precipitates were evident in the storage water at Savannah River storage facility, prompting concern about the potentially rapid degradation of the SNF protective coating, and subsequent chemical and biological investigations.[16] While total organic carbon (TOC) in the storage water was 6.8 mg/l (avg., SD + 12.5), the TOC in the precipitate was 883 μg/g (wet wt.). Major elements associated with the white precipitate were silicon, aluminum, titanium, and Fe. Bacterial 16S rRNA phylotyping revealed the presence of *Aquabacterium, Hyphomicrobium, Pedomicrobium, Rhodoplanes* bacterial genera, and representatives from the *Burkholdariaceae* family.

Methylated I-129 can be transferred from water and ocean systems to the atmosphere for increased dispersion. Two novel strains of *Roseovarius* (closest known relatives to R. *tolerans*) were isolated from seawater and marine mud, and demonstrated to generate forms of methylated I using GC-MS.[17] Motivated by this same public health concern, other researchers have demonstrated and quantified the biogenic methylation of I-129 by specific marine bacteria: *Alteromonas macleodi*i IAM 12920, *Deleya marina* IAM 14107, *Photobacterium phosphoreum* IAM 14401, *Photobacterium leiognathi* NCIMB 2193, *Pseudoalteromonas haloplanktis* IAM 12915, *Shewanella putrefaciens* IAM 12079, and *Vibrio splendidus* NCIMB 1.[14]

Air and Space Microbiomes. In principle, microbiome populations in air can be useful as a tool to detect nuclear or other contaminants, provided we know the patterns of their dynamics. However, among studies on environmental microbiomes, air and space microbiome populations have been least studied. In the following sections, we provide a current view of air and space microbiome research and discuss how it could be applied to the monitoring needs discussed herein.

Atmospheric Microbiomes. Microorganisms in airborne biomes vary in concentration, ranging from approximately $3.9x10^2$ – $1.2x10^3$ cells per m^3 in forests and $7.9x10^2$ – $7.2x10^3$ cells per m^3 in urban settings, to as high as $1.9x10^7$ – $1.0x10^9$ cells per m3 during agricultural activities associated with bailing and combining.[18] About 25% of airborne particulates are biological, including pollen, fungal spores, bacteria, viruses, and so on. Weather conditions control, to a degree, microbial transport with the vertical concentration of bacteria declining much less than fungal spores.[19] Microbial retention in the atmosphere is extended through contact with water droplets in clouds. About 15% of the volume of the first 6 kilometers of the atmosphere is occupied by clouds[20], thus the atmosphere harbors an enormous transient population of microbes.

The potential for the large transient population of microorganisms passing overhead to serve as environmental monitors should be explored more thoroughly. Highly concentrated samples can easily be obtained through conventional air sampling devices and could provide a magnified analytical sample related to covert activities. Sampling can be easily achieved by, e.g., capture of ambient air using conventional air sampling devices and collecting rainwater.[21] In addition, under conditions of sufficient moisture and temperature as well as available carbon and energy[22], evidence has been produced showing microbes can grow[23] and even thrive[24] in cloud water. The most metabolically active members of cloud microbiota were identified as Alpha- (*Sphingomonadales, Rhodospirillales* and *Rhizobiales*), Beta- (*Burkholderiales)* and Gamma-Proteobacteria (*Pseudomonadales*). Also, common isolates from cloud water are the genera *Deinococcus* and *Spirosoma*, known for their high resistance to DNA-damage like that caused by UV light and gamma radiation.[24-26] Given the relative nutrient scarcity of cloud water (compared to groundwater or other terrestrial niches), transcriptomic as well as other analytical approaches targeting metabolic output and function may best highlight changes among these microbiota.

<u>Indoor Microbiomes.</u> Indoor air consists of a variety of solid aerosol particles, including inhalable bioaerosols, which recently have been the focus of scientific research because of their impacts on public health due to COVID-19.[27] In the present section, we cover a broad range of microbiome samples from air in different enclosed spaces such as houses, subways, office buildings, and even in areas with low gravity and high radiation such as found in the International Space Station (ISS).[28]

Microbiome populations sampled in subways have high representation of typical skin microbes, but the dynamics of this microbiome are influenced by levels of carbon dioxide, temperature, and time of day.[29] Microbiome population studies in residences reveal similarities between indoor microbiome compositions and surrounding outdoor environments. The composition slightly differs depending on the frequencies and sources of ventilation, as well as the number of people living in the residence whose skin microbiome contributes to the variation. Additionally, the frequency of vacuuming can increase representation of the floor microbiota in the sampled air.[30] While the fungal portions of air microbiome samples also resemble outdoor populations, they have dispersal limitations due to the increased size and weight compared to bacteria and viruses.[31] As such, they might be a more stable tool for verification of nuclear materials. For instance, the high radiation absorption capacity of gilled fungi (mushrooms), suggests airborne fungi spores would be worthwhile tools30. Interestingly, observations of ISS surface microbiomes revealed they are heavily influenced by astronauts' microbiome and are not easily changed even after the individuals' departure.[32] Such organisms, including those inside of the ISS where they are subject environmental stressors like radiation and microgravity, have been a focus of studies during recent years.[32,33] Determining whether collection of microbiota from surfaces and air represents a useful tool for radiation monitoring merits additional research.

<u>Studies on Radiation Effects: Differences by Distance.</u> Some studies, including those evaluating the impacts of both the Chernobyl and Fukushima accidents, have focused on radiation effects as they relate to distance from exposure sources.[34-38] A notable study focusing on soil microbiome highlighted increased Cs-137 concentration upwards of 1 km from the Chernobyl power plant (10-563,000 Bq Cs-137/kg dry soil). Further, analysis of community diversity showed that distance and contamination were significant influences on the microbiome structure of sampled sites. Community compositional profiling of the most contaminated sites revealed increased abundance of radioresistant *Geodermatophilus bullaregiensis*.[35] For those sites, the vast majority of radioactive contamination results from americium-241 (recently discovered), cesium-137, strontium-90, and iodine-131. Studies on earthworms from the Chernobyl exclusion zone (CEZ) have shown no significant differences in oxidation and other radiation impacts, but the authors recommended that soil microbiome studies may better elucidate differences that depend on ex-

posure to variable radiation levels related to distance from primary sources.37 Although such efforts are very limited and nascent, increased focus will undoubtedly reveal their utility.

Microbiomes in Extreme Environments. "Extremophiles" are microorganisms that inhabit environments where the conditions are marked by extremes of temperature, pH, salinity, pressure, or radiation that are often inhospitable to most life forms. The cellular and metabolic machinery of extremophiles have evolved to withstand challenging environmental conditions, making them attractive candidates for biotechnology applications. A classic example is the discovery of a heat-stable DNA polymerase isolated from *Thermus aquaticus*, a microorganism originating from Yellowstone National Park, USA[39], and its adoption for use in polymerase chain reactions to assist the replication of DNA.[40]

Isolation of extremophile microorganisms can be complicated, as the environment itself might be dangerous or logistically challenging for sampling and/or the extreme conditions or mixture of substrates for cultivation might be difficult to achieve. Nonetheless, they are a significant part of the "microbial dark matter" that has yet to be discovered[41] and undoubtedly will offer unique insights into new metabolic pathways and survival strategies for future research.

Certain microorganisms such as *Deinococcus*, *Spirosoma*, *Rufibacter,* and *Hymenobactertibetensis*[42] have self-repair mechanisms making them resistant to denaturing effects and oxidative damage outcomes related to radiation exposure.[43] For instance, *Deinococcus radiodurans* is an extremophile capable of surviving ionizing and ultraviolet radiation that are lethal to humans[44], it was originally isolated from canned meat that was exposed to X-irradiation.[45] Additionally, *Chroococcidiopsis*, a cyanobacterium, employs quick and efficient DNA repair mechanisms to resist damaging effects due to IR.[46]

Microalgae have been found to successfully fractionate uranium isotopes.[47] Moreover, fungi are capable of immobilizing radionuclides.[48] For example, fungi such as *Cladosporium cladosporioides* and *Penicillium roseopurpureum* decomposed radioactive debris caused by the Chernobyl reactor within 50 to 150 days.[49] Melanin, a natural pigment produced by some fungi, may have helped to mitigate the deleterious effects of radiation.[50] Melanized fungal species colonized the walls of the Chernobyl reactor and exhibited growth toward radiation, perhaps using it as a nutritional source.[51]

It is common to find microorganisms, termed "*polyextremophiles*", capable of withstanding multiple harsh conditions in water and soil matrices contaminated by effluent from nuclear processes. Culturing techniques that replicate a combination of extremes (e.g., presence of heavy metals and concomitant low pH) prove helpful to isolate them.[52] Polyextremophiles and their metabolic products have been evaluated for their potential to act as microfactories for metal and radionuclide remediation of contaminated soil and water.[53] They could be used as natural sentinels or as sensor elements in hybrid detection devices to provide indication of anthropogenic activity.

Tertiary (Non-Radioactive) Compounds as Microbial Influencers. Previous sections provided evidence that microbial communities can sense and respond to the presence of radionuclides and that the signal is potentially retained after the radioactivity is no longer detectable or the radionuclides have been removed. It is plausible to posit that microbial communities will also respond to other materials, including industrial chemicals, which may be present as a consequence of nuclear activity. Although there are numerous compounds used for diverse types of nuclear materials extraction, featured here is a smaller list of compounds that are commonly used as part of well-established protocols like plutonium uranium reduction extraction (PUREX).[54]

One of the main solvents used in the PUREX process is tributyl phosphate (TBP), an industrial solvent with toxic, corrosive, and carcinogenic properties. A number of bacteria from the genera *Alcaligenes, Providencia, Delftia, Ralstonia*, and *Bacillus* have been isolated that can grow on TBP as the sole carbon (C) and phosphorus (P) source[55], showing degradation in laboratory cultures of >50% from 5 mM TBP after 4 days. Soil samples from a uranium mine, containing complex microbial communities, were incubated in the laboratory with 1,000 ppm TBP and other carbon sources. Upwards of 60% of the TBP was removed in 4 days and 80% in 10 days.[56] However, TBP is not a commonly utilizable source of plutonium (Pu), particularly for marine bacteria. A recent study evaluating bacterial growth on 22 organic Pu pollutants found that none of the 17 tested strains could grow on this compound.[57] Research examining the influence of TBP on microbial community structure are presently lacking. As such, field contamination studies to monitor microbial communities in plots (for soil and sediments) or mesocosms (for aquatic systems) amended with different concentrations of TBP are necessary to determine whether TBP contamination yields observable and distinctive changes.

Another compound commonly used in nuclear processing is nitric acid (HNO_3), which results in high concentrations of nitrate and eventually nitrite in effluents. An early study documented microbial changes, including reduced community diversity and alterations of taxa, at sites contaminated with nitrate, nickel, aluminum, and uranium.[58] A subsequent study examined a similarly contaminated groundwater community with metagenomics[59], finding genes specific to resistance for nitrate, heavy metals, and acetone. Due to the presence of multiple contaminants (nitrate, nitrite, heavy metals, other organics), it was not possible to attribute observed microbial responses to a specific compound. However, a more recent study found that members from genus *Bacillus* dominated in soil community following direct additions of HNO_3[60]. With regard to nitrate contamination and its impact on microbial communities, substantial literature exists, and includes references to the nitrogen cycling genes required for the biological removal of heavy metals, including radionuclides, implicated in nitrate and nitrite reduction.[61] Nitrate contamination can result from other processes and practices (e.g., agricultural practices), but identification of microbial community changes combined with orthogonal detection schema to characterize any additional contaminating agents could yield information indicative of nuclear reprocessing and associated with the specific process that is being used.

Hyrdrofluoric acid (HF) is likewise used in the PUREX process. Unlike HNO_3, HF dissolution does not result in the production of a macronutrient like nitrate, thus HF microbial signatures may be more specific to industrial contamination like that resulting from reprocessing. One study used cultivation-dependent methods to examine soil bacteria at different distances (3, 7, and 20 km) from a source of HF and found decreasing soil respiration, biomass, and culturable bacteria as the samples got closer to the pollution source.[62] A subsequent study evaluated soil samples incubated with increasing HF concentrations in the laboratory for up to 10 days and found, not unexpectedly, that certain taxa increased in relative abundance, and others decreased in response to HF treatment.[63] Recent work also examined the impact of HF contamination on soil microbial communities60, finding that the genus *Bacillus* and other acidophilic (acid-loving) microbes became numerically dominant.

Kerosene and oxalate used in the PUREX process may also produce changes to microbial communities. Both are organic compounds that can be used by microbes as a source of carbon for growth and/or respiration.[64,65] Oxalate-degrading bacteria are more common, since this compound is released into the soil by plants and into the gut by animals[66], whereas kerosene degradation is a less common phenotype associated with degradation of hydrocarbons. A significant amount of literature exists regarding the effects of kerosene on microbial community structure because it is a common hydrocarbon pollutant, and the genes involved in kerosene degradation are well-characterized.[67] Conversely, oxalate pollution is uncommon, and literature surveys reveal no relevant literature with respect to the impacts, if any, environmental oxalate contamination may have on microbial communities.

Although numerous articles detail microbial response to TBP, HF, HNO_3, kerosene, and oxalate, most of the work, with a few exceptions, has interrogated naturally polluted sites or evaluated changes associated with laboratory enrichment experiments. A fully factorial ecotoxicology experiment where different toxic components, including radionuclides, are added individually and in combination to soil plots and aquatic mesocosms would be of high value. To develop a more comprehensive understanding that extends to multiple ecosystems, studies that replicate the work in different soil and water matrices with different geochemistries would be required.

Section Summary. It is logical to speculate that microbes and microbiome communities can serve as unique, sensitive natural sensing systems based on a number of qualities:

- Microbiomes exist in nearly all environments.
- Microbes, either as individual species or as diverse communities, respond to environmental perturbation with physiological, biochemical, genetic, and epigenetic as well as community composition and functional changes.
- Changes can be leveraged as signatures for detection and monitoring applications.
- Unique microbial features such as the ability to live in extreme conditions can be exploited for developing novel sensing motifs.

The studies delineated here represent various environmental systems affected by radiation, chemical, and metal sources and established use cases for monitoring scenarios. Additional work will bolster previous results in addition to providing new data that support deeper and more precise inferences. For example, whole genome assemblies would produce more taxonomic resolution (e.g., strain level variation). The combination of other 'omics technologies (i.e., proteomics, metabolomics, transcriptomics, etc.) with next generation sequencing (NGS) may offer resolution at the species, strain, and functional levels; however, these combinations are still fairly new, and good reference databases that allow adequate annotation are not fully formulated. Whereas such challenges are daunting, the collective body of work to date laid the foundation for the next phase of microbiome research that seeks application rather than phenomenology. The sections above, while not exhaustive or systematic, provide a glimpse into these efforts and offer potential targets for more focused approaches to address the questions surrounding environmental microbiomes and their potential to act as sentinels for ecosystem change.

Multicellular Organisms and Biologically-Derived Materials

Plants as Sentinels for Detecting Nuclear Processes

Plants have a number of features that make them promising candidates to serve as sentinels for detection of illicit nuclear activity, or more generally, unexpected IR exposures. By virtue of their generally sessile life-cycle, plants must respond to environmental threats *in situ*. As a result, many plant species have evolved robust responses to a wide range of biological or abiotic stressors.[68,69] Characterizing and understanding the sensitivity and specificity of these responses could facilitate harnessing them as indicators of radiation or nuclear material exposure. Chemicals, radiation, or thermal energy released into the environment by nuclear activities may alter the plant species distribution within the local area or lead to spectral changes in vegetation.[70,71] Plants display a range of lifespans allowing historical sampling, potentially over long periods of time. During these lifespans, they are constantly sampling the air and groundwater as well as interacting with microbial communities present on leaves and roots. Thus, they have the potential to serve as bioaccumulators of compounds in the environment. Furthermore, certain plant species have been identified that hyperaccumulate metals and radionuclides, thereby serving as natural amplifiers and collection devices.[72,73] Plants have been shown to have long-lasting biological changes, known collectively as 'plant memory', which may provide signatures of chemical or radiation exposure when no direct chemical or physical signal remains in the environment.[74] Plant memory includes protein, transcript, and epigenetic changes. Detection technologies leveraging plants as described above will require physical collection and analysis of plant tissue. However, some plant responses, such as changes in plant distribution and spectral signatures, may be monitored using remote sensing techniques. The present section provides a review of current data on the ability of plants to sense, signal, and respond to IR, nuclear, and process materials that reside in the environment and means by which such information might be used.

Changes in Plant Species Distribution as Indicators of Radiation Exposure. Ecological studies have documented significant changes in species distribution within the natural environments surrounding the sites of several nuclear power plant accidents, including Kyshtym, Chernobyl, and

Fukushima, as well as contaminated processing sites like the Oak Ridge National Laboratory site and the Mayak plutonium plant area.[75-79] The Kyshtym and Chernobyl accidents both resulted in vegetation death at areas receiving high doses of radiation. At the highest radiation doses (60 – 200 Gy), tree death was observed, with coniferous trees showing greater radiosensitivity than deciduous trees.[75,76,78] Moreover, specific tissues such as the buds and needles were more susceptible to radiation damage. As a result, forest growth and recovery was also impacted, with birch replacing pine in the areas around Kyshytm and Chernobyl.[75,78] At high radiation doses (30-50 Gy), herbaceous plant death was observed, with species death corresponding to radiosensitivity, phase of life cycle at the time of exposure, and the effective dose rate based on exposure route, including gaseous deposition through the air, soil surface exposure, or transport of the radionuclide through the roots.[75,80] At moderate radiation doses (5-10 Gy), plant death did not occur; however, there were visible signs of stress, like abscission of needles and damage to reproductive buds.78 Furthermore, suppression of vegetation growth was observed at lower radiation doses (0.5 – 1 Gy)[75,78,] and an overall reduction in biodiversity was observed in all ecosystems surrounding the sites of nuclear power plant accidents.[75,77]

The release of radionuclides from small-scale or clandestine nuclear processes is likely to be significantly lower than that released by the aforementioned nuclear power plant accidents[81] At these radiation doses, ecological succession resulting in presence, absence, or changes in abundance of particular species within the surrounding environment is unlikely. However, more sensitive and subtle plant changes, including reduced growth rates as well as spectral, protein, transcript, and epigenetic changes, may serve as indicators of anthropogenic activity. If there is a significant release of radionuclides into the local environment, changes to native flora based on radiosensitivity may serve as a remote indicator, as described above. A list of radiation-resistant plant species is shown in Table 2.[79] Radiation-resistant plant species were generally shown to have smaller genomes and concomitant high tolerance to heavy metals. It is worthwhile to note that changes in plant species within the environment will be complicated by other factors including the composition of the soil, which will affect the bioavailability of the radionuclide, and the availability of nutrients, which will impact plant stress response and survival. Therefore, environmental modeling and machine learning will likely play important roles in using plant species as indicators of nuclear activity.

Plant Taxa	**Genome size (Mb)**	**Location of Study**
Willow trees (genus *Salix*)	~425-429	Chernobyl, Oak Ridge, Fukushima, Canada
Birch trees (genus *Betula*)	~430-600	Chernobyl, Kyshtym
Alder trees (genus *Alnus*)	513-983	Chernobyl, Canada
Aspen trees (genus *Populus*)	440-593	Canada, Chernobyl
Sedges (genus *Carex*)	~150-300	Chernobyl, Mayak, Oak Ridge, Fukushima
Raspberries and related species (genus *Rubus*)	291-308	Fukushima, Canada, Chernobyl
Sorrels and related species (genus *Rumex*)	3200-3700	Chernobyl, Fukushima
Common reed (*Phragmites australis*)	~470-560	Mayak, Chernobyl

Table 2 . Radiation-resistant plant species identified through prior environmental monitoring studies.[79]

<u>Optical Spectroscopy for the Detection of Nuclear Chemical Effluents in Plant Sentinels.</u> The U.S. Government investment in next-generation hyperspectral imaging (HSI) systems has expanded the application of spectral signatures to determine process activity. HSI data provides high spectral content and is spatially mapped to show the distribution of vegetation exposed to source emissions from nuclear processing facilities. The advantage of using plant sentinels from an optical remote sensing perspective is that they are stationary and provide a persistent signal. Remote sensing and data collections over denied areas are usually episodic events and the ability to time source re-

leases to collection periods is a major shortcoming. Once vegetation uptake response from known process source emissions can be related to a reflective spectral response, plant sentinels could be used as *in situ* indicators for detection and monitoring using non-contact, passive remote sensing optical techniques.

A key gaseous phase source emission, HF, is transported through the atmosphere to expose vegetation species through leaf structure absorption.[82] Taylor et al. published a seven-year study (1972-1978) that evaluated fluoride air emissions and the potential vegetation impacts at the Paducah Gaseous Diffusion Plant (PGDP).[83] Continuously operating air sampling stations provided seven day averaged air samples of HF, and fluoride concentrations were measured in *Festuca arundinacea Schreb* sample collected from the surrounding grass areas. While air concentrations of HF varied from 0.01 to 24.5 µg (HF)/m³, fluoride concentrations in the grass measured as high as 1,000 µg/g near the PGDP and approximately 100 µg/g at distant locations. Similar relationships between F air concentrations, plant uptake and distance (>10 km) from emission source were found in studies of aluminum smelters.[84]

The use of spectral reflectance to study photosynthesis and related vegetative processes has been ongoing for decades[85,86], and numerous vegetation indices and algorithms have been developed to estimate plant stress factors and physiological conditions. An example of relevant research is the Combined Vegetation Index (CVI) developed in the context of a South Korean HF explosion accident.[87] In this study, remote sensing HSI data were utilized to interrogate foliage damage caused by the sudden and accidental release of HF. The deployed HSI system had a spectral range from 360 to 1,047 nm. Detailed spectral analysis of the data indicated that fluctuations occurred between 786 nm and 801 nm in the HF-affected vegetation. The study demonstrates that HF exposed vegetation detection is possible using HSI techniques; however, it also illustrates that more work is needed with higher resolution spectrometers that have a wider spectral range in order to deal with potential confounding stress factors so that the F-signal is definitive.

Other source emissions from industrial facilities are in the form of solids, including heavy metals, and liquids that exit through waste streams and accumulate in local vegetation. Metal-vegetation interactions, as measurable through optical remote sensing techniques, have been researched

Key Features/ Index*	Formula	Metal(s)	Vegetation Type	Ref.
CR_{1730}	--	General HM	Floodplain	91
DVI	$2.4(MSS7 - MSS5)$	Ni, Cd, Cu, Pb, Zn	Floodplain, ryegrass	92
EGFN	$\frac{Max(R650' - R750')}{Max(R500' - R550')}$	Zn	Conifer	93
NDVI	$\frac{R800 - R670}{R800 + R670}$	Cr, Pb, Zn, V	Gray birch	94
		Ni, Cd, Cu, Pb, Zn	Rice	95
		Hg	Mustard spinach	96
NPCI	$\frac{R680 - R430}{R680 + R430}$	General HM	Stinging nettles, Reed canary grass, Meadow foxtail	91
PRI	$\frac{R531 - R570}{R531 + R570}$	General HM	Floodplain	91
		As	Ferns	97,98
		General HM	Stinging nettles, Reed canary grass, Meadow foxtail	91
R_{850}	--	Cd, Cu, Pb, Zn, As	Peas	99
R_{1650}	--	Cd, Cu, Pb, Zn, As	Peas	99
R_{2200}	--	Cd, Cu, Pb, Zn, As	Peas	99
REP	$Max(R690' - R740')$	Ni, Cd, Cu, Pb, Zn	Floodplain, ryegrass	92
		Pb	Rice	100
		Cu	Peas, maize	101
		Zn	Sunflower	101
		General HM	Floodplain Bluegrass, ryegrass	102,103
		Hg	Mustard spinach	96
		General HM	Stinging nettles, Reed canary grass, Meadow foxtail	91
RGI	$\frac{R695}{R554}$	Cr, Pb, Zn, V	Gray birch	94
RVI	$\frac{Red}{Near\ Infrared}$	Hg	Mustard spinach	96

*CR = Continuum Removed; DVI = Difference Vegetation Index; EGFN = Edge-Green First Derivative Ratio; NDVI = Normalized Difference Vegetation Index; NPCI = Normalized Pigment Chlorophyll Index; PRI = Photochemical Reflectance Index; R = Reflectance; REP = Red Edge Position; RGI = Red Green Index; RVI = Ratio Vegetation Index

Table 3: Key spectral features and vegetation indices related to metal stress in the literature.[104]

primarily in the agricultural and ecological sciences. Notable spectral features and vegetation indices related to metal stress found in literature are summarized in Table 3. Hexavalent chromium (Cr(VI)), a heavy metal associated with the nuclear industry, has been widely researched. Cr(VI) species are mobile in the environment and readily taken up by plant roots[88,89] Chromium induces decreases in photosynthetic pigments chlorophyll-a, chlorophyll-b, and carotenoids.[89] Reflectance spectroscopy was applied to study the effects of chromium on the Chinese brake fern (*Pteris vittata*), and a unique ratio index ($R_{1110/}R_{810}$) was identified to differentiate Cr(VI)-exposed ferns from arsenic-stressed ferns and a control.[90]

In addition to identifying specific wavelengths and spectral indices, other analytics and machine learning approaches may further enable the detection of plant spectral features as indicators of radiation or chemical exposure. For example, hyperspectral reflectance imaging and multivariate curve resolution alternating least squares analysis was applied to *Arabidopsis* to identify unique spectral features to differentiate Cs stress from two other stress phenotypes resulting from exposure to salt and copper.[105]

A central point, and one that is reiterated multiple times throughout the present article regardless of the system or method of interrogation, is the need to isolate features associated with the uptake of the source emission versus stress indicators caused by naturally occurring environmental factors. Research should be guided by robust experimental protocols in order to verify the relationship between source emission, plant uptake, and spectral reflective response. In this regard, useful work includes co-stressor experiments, which combine source emission exposures and environmental stress factors, for different vegetation species, and application of advanced microscopy methods to assess plant physiological changes to quantify spectral reflective response.

Plant Accumulators for Collection of Radionuclides. Plants have been extensively studied for their ability to uptake and sequester heavy metals, including radionuclides.[71,73,80,89,106-132] While many studies have focused on the potential of plants for bioremediation of contaminated sites, these plant species may also be used as natural accumulators for detection of nearby nuclear processes. Examples of plant accumulators for certain chemicals associated with nuclear processes are listed in Table 3. It is important to note that the accumulation levels reported in Table 3 are dependent on the exposure dosage, so accumulation measurements are not directly comparable to source terms. However, the list nonetheless provides proof-of-principle that plants can be used as monitoring systems which have particular utility for tipping and cuing as well as broad area surveillance. In addition to the examples provided in the table, plant species such as *Sebertia acuminata, Arabidopsis halleri, Thlaspi caerulescens, Thlaspi praecox,* and *Solanum nigrum*, have been shown to hyperaccumulate other metals like nickel.[73,122] Manipulating the mechanisms of metal hyperaccumulation to enable radionuclide accumulation in species like these could be a fruitful area of research. As discussed in the previous section on *Changes in Plant Species*, environmental factors and soil chemistry play a key role in uptake and transport of chemical species. For example, the addition of organic acids like citrate to soil have improved uranium uptake in several Brassica species by more than 1000-fold.[117]

Chemical accumulation in plants has been studied extensively for environments surrounding nuclear accidents as well as nuclear power plants, providing data for a wide range of plant species and exposure levels. However, only a limited number of plant species were analyzed in each study, and crop species were a primary focus due to potential human health effects. Furthermore, the high number of environmental variables in field studies makes it challenging to predict chemical accumulation in plant species for a specific environmental scenario. Future research efforts would benefit from focusing specifically on indigenous plant species relevant to regions of interest and developing high-throughput laboratory techniques combined with machine learning to understand the influence of environmental variables as well as to identify plant species best suited for accumulating signatures of interest.

Chemical	Accumulating plant species	Level of measured accumulation	Ref.
Americium	*Elodea canadensis*	Up to 3,280 Bq/g dry weight (^{241}Am)	106
Cesium	*Petasites japonicus*	Up to 78 Bq/kg dry soil of ^{137}C	129
	Gypsophia paniculate	7339.49 mg/kg dry weight	132
	Helianthus annuus L. (sunflower)	Up to ~2,700 Bq/mg dry weight	125
Chromium	*Dicoma niccolifera*	1.5 mg/g dry weight	116
	Suteria fodina	2.4 mg/g dry weight; 48,000 ppm	116
	Leptospermum scoparium	2,470 ppm	116
Neptunium	*Fontinalis antipyretica* (moss)	Up to 1490 Bq/kg	108
	Alfalfa	Concentration ratio of 4.2 with 2.6 x 10^{-6} mg/g Np	111
Plutonium	*Fontinalis antipyretica* (moss)	Up to 4.1 Bq/kg	108
	Brassica juncea (Indian mustard)	Up to 1699.1 Bq/g in shoots; up to 24,785.3 Bq/g in roots (^{239}Pu)	118
	Onion moss	24.27 Bq/kg (^{238}Pu), 52.78 Bq/kb (^{240}Pu)	110
Strongtium	*Picea excelsa*	Up to 328.42 ppm in needles	121
	Parthenocissus quinquefolia	262.2 µg/g	119
	Helianthus annuus L. (sunflower)	Up to ~4,500 Bq/mg dry weight	125
Tritium	Apple	Up to 96.1 Bq/kg	128
	Potato	Up to 208.0 Bq/kg	128
	Parmelia sulcate	Up to 4460 Bq/kg	131
	Evernia prunastri	Up to 6020 Bq/kg	131
Uranium	*Picea excelsa* (spruce tree)	Up to 310.86 ppm in roots	121
	Cyperus iria	38.83 µg/g	119
	Juncellus serotinus	37.7 µg/g	119
	Water lily	1538 mg/kg in root; 3446 mg/kg in aerial tissue	112
	Mustard	7145 mg/kg in root; ~380 mg/kg in aerial tissue	112
	Ryegrass	~980 mg/kg in root; ~600 mg/kg in aerial tissue	112
	Bidens pilosa	721.46 mg/kg in root; 661.36 mg/kg in aerial tissue	112
	Wild stonecrop	~800 mg/kg in root; ~1600 mg/kg in aerial tissue	112
	Purple sweet potato	5712 mg/kg in root; 3.48 mg/kg in aerial tissue	112
	Brassica juncea and *Brassica chinesis*	> 5,000 mg/kg in shoots	117

Table 4. Plant accumulators of chemicals associated with nuclear processes.

Harnessing Transcriptional Effects of Ionizing Radiation on Plants. IR-induced changes in gene expression offer a promising potential tool for detection. Gene expression, including variation in transcript or exon usage, may be identified by RNA sequencing methods that can be applied either in the laboratory or in the field. The large numbers of genes in a typical plant transcriptome provide multiple detection opportunities either focused on specific genes or via broad, multigene fingerprints or profiles. Plants are known to modulate gene expression in response to a wide variety of biotic and abiotic stressors, whether chronic or acute in nature. While there is a long history of experimental and observational studies of the effects of IR on gene expression in plants, consistent and widely applicable conclusions are difficult to draw from the literature.[133-136] Difficulty arises from the diversity of plant species that have been studied, differing developmental stages at which experimental radiation has been applied, and variability in the populations and sites at which they were grown. There is also considerable variation in the quality, dose, and duration of radiation exposure in experimental systems as well as in the timing of sampling post-exposure. Much of the available data derive from less well controlled, non-experimental systems such as sites such as Chernobyl[137], overt attempts to generate new varieties for agribusiness[138,139], and food sterilization applications.[140] Finally, many studies have relied on older, array-based systems or targeted studies of specific genes in assessing IR effects on gene expression in plants.

At relatively high acute doses of external gamma radiation exposure (e.g. ≥100 Gy), a wide variety of genes active in abiotic and biological stress responses or metabolism are reported to display altered expression.[141,142] These include genes involved in DNA damage and oxidative stress responses, among others.[143,144] Kovalchuk et al. also observed upregulation of DNA damage and oxidative stress response genes in *A. thaliana* when exposed to lower doses of gamma radiation (e.g. 1.0 Gy) but only for acute doses.[145] Sugimoto *et al*. compared the transcriptomes of *B. rapa* plants (Mizuna) grown on the International Space Station to those grown on the ground.[146] They observed significant differences in the expression of genes that are responsive to reactive oxygen species, as might be induced by space irradiation, including gene expression changes that were unique to the space-grown plants. In our own unpublished studies (Zhou *et al.* (in preparation)), we have examined transcriptional responses at lower doses of gamma radiation (from 1.4 cGy to 1.0 Gy) in multiple plant species and observed that the number of genes with significantly altered expression upon exposure increases with decreasing dose, suggesting that there may be opportunities for detecting IR exposure at low doses through transcriptomic assays.

RNA sequencing (RNA-seq) approaches provide the opportunity to generate highly quantitative data on gene and transcript expression in response to stressors such as IR and with minimal tissue requirements. The ability to "fingerprint" transcriptional responses offers the potential to disentangle gene expression changes that may be specific to IR exposure from other confounding and more generalized stress responses. However, before transcriptional data can be used to reliably detect radiation exposures or to provide dosimetry, further characterization of transcriptional responses to IR in plants needs to be performed. This would include surveying of ubiquitous plant varieties that could serve as broadly distributed sentinels. Plants in the genus *Brassica* are one potential candidate. There are more than 30 species of *Brassica*, some of which are cultivated (mustards, cabbages), but most of which grow wild on every continent except Antarctica. Alternatively, conserved pathways or genes that respond to IR across species would need to be identified and characterized. Regardless of the plant species or gene targets chosen as potential sensors, transcriptional responses need to be characterized at different doses and dose rates, as well as in different tissues and for different types of exposures.

<u>Epigenetic Responses to Ionizing Radiation in Plants.</u> An alternative to quantifying transcripts produced by genes in response to IR exposure is to examine the actions of factors that regulate the expression of these genes. Such factors could include alterations in DNA methylation, chromatin accessibility, histone modifications, or altered expression of non-coding RNAs.[147] Among these different factors, DNA methylation is of particular interest because it has the potential to be maintained over long periods of time and, indeed, may be maintained transgenerationally.[148,149] Plants, in general, tend to have higher overall levels of DNA methylation than other organisms but with considerable variation between species.[150] Prior studies of the effects of IR on DNA methylation in plants have primarily utilized older approaches that survey only limited portions of the genome, such as digestion of genomic DNA with methylation-sensitive restriction enzymes, and methods of detection such as Southern blotting or radioactive nucleotide incorporation[137,151], that have modest sensitivity to detect changes, particularly when those changes occur in only a limited number of cells in a given tissue. In contrast, current genomic technologies, such as sequencing of bisulfite or enzyme modified genomic DNA or direct detection of modified nucleotides, allow comprehensive detection of methylated sites across the genome, while the ability to sequence at depth allows the detection of changes occurring in relatively small numbers of cells in a population.

Only a few published studies have examined variation in DNA methylation in response to IR in plants. Kim *et al*. noted decreasing methylation, primarily at CHH and CHG sites, with increasing gamma radiation doses from 5-200 Gy.[152] Caplin et al. noted reductions in global DNA methylation in *A. thaliana* in response to chronic exposure to Cs-137 (40 µGy/hr) over two generations but only in the exposed generations. Ou *et al*. examined the effects of spaceflight on methylation in *Oryza sativa* (rice).[151] Although these studies are potentially confounded by other factors, such as microgravity or magnetic fields on plant stress levels, it was observed that DNA methylation at the small number of sites examined (< 20) was generally increased. These results are in agreement with the observations of Kovalchuk *et al*., who also reported generally increased levels of DNA methylation in native *Arabidopsis* collected from the Chernobyl exclusion zone that had estimated absorbed doses in the range of 0.2-2 Gy.[137] While these studies suggest an overall trend towards hypomethylation of DNA at cytosine residues in response to IR exposure, it is important to recognize that the effects of DNA methylation are site-specific. Overall increases or decreases in methylation may mask critical shifts in methylation with regulatory consequences for specific genes. This suggests that targeted assays for methylation changes at specific sites, validated by transcriptomic or proteomic studies of the associated gene(s) and their product(s), may be more efficient and sensitive as a tool for detecting exposure to IR.

Section Summary. As detailed in the above sections, plants have great potential to be exploited as natural sentinels for nuclear activities. However, several overarching challenges have thus far prevented the use of plant sentinels in an operational context. Biological and environmental variables often have confounding effects. For example, a particular plant species may respond differently at various stages in its growth cycle or under seasonal environmental conditions. Plant responses may also differ depending on the dose or biological availability of the chemical species, which is affected by meteorological conditions and soil composition. Plants can also develop non-photochemical quenching responses to some external exposures which offers additional challenges, particularly for remote sensing. Lastly, some responses are generalizable to multiple stressors, thus producing non-specific signatures. Limited understanding of plant responses constrains, at present, utility for some applications. Only a small subset of plant species has been studied as potential sentinels, with many of these studies focusing on natural species found near nuclear accidents. Moreover, some biotechnologies, such as sequencing technologies for detecting epigenetic modifications, are recent developments. Finally, operational constraints may be a limitation if physical access to the site is required for collection of plant material; however, optical spectroscopy and remote sensing has shown promise that may increase their utility once proof-of-concept is more firmly established.

Native and Domesticated Animals

Animals are sensitive to environmental perturbation and have been extensively studied as sentinels of ecosystem change, particularly that related to anthropogenic disturbance.153 Analyses can include both qualitative and quantitative approaches to assess morphological and pathological changes; to interrogate excreta, bodily fluids, tissues, and biomaterials for contaminant residues; to evaluate genetic damage, metabolic changes, enzymatic markers, and other molecular endpoints related to exposure; and to analyze community- and population-level changes like species composition, density, and diversity.154,155,156 These methods provide an additional source of intelligence that serves as a "tipping and cueing" function or as an orthogonal means of verification.

Morphological and pathological changes. Environmental radiation exposure can, in some cases, produce observable changes to physical traits that do not require sophisticated analytical tools for interpretation. So-called "epigenetic" factors modulate gene expression based on both endogenous and exogenous cues, including to, *e.g.*, exposure to IR and chemicals, that can manifest as distinctive phenotypic modifications.[157] Proof-of-concept is provided in several epigenetic studies that examine the influences of *in utero* exposure to gamma radiation. For example, the Viable Yellow Agouti (A^{vy}) mouse model was used as a bioindicator for low-dose IR exposure (<0.1 Gy).[158] Exposure to IR resulted in sex-specific changes to gene methylation patterns that concomitantly altered coat color and reduced body mass. Moreover, exposure produced changes that were dose-specific.

Other studies in both Fukushima and Chernobyl underscore the importance of phenotypic changes as indicators of environmental radiation exposure. Butterfly larvae developed obvious physical malformations upon metamorphosis after ingesting leaves from sites contaminated with IR from the Fukushima accident.[159] Dose levels as low as 0.2 Bq/kg produced notable changes as compared to control groups. Chernobyl researchers made similar observations, identifying morphological abnormalities mediated by a phenomenon known as "fluctuating asymmetry" in stag beetles160 and barn swallows161 from sites contaminated with Sr-90 and Cs-134,-137. More recent studies on animals from the Chernobyl Exclusion Zone indicate that exposure to low, chronic doses of IR resulted in notable changes to heart, kidney, and brain mass.[162]

Multiple lines of research thus demonstrate that environmental exposure to IR is sufficient to elicit perceptible changes, although the nature and extent of such changes may vary according to the particular organism under study. Special consideration should be given to selection of species whose feeding ecologies and other lifestyle factors contribute to enhancement of absorbed dose and/or who are more inherently susceptible to IR effects.

Excreta, bodily fluids, tissues, and food products. Systems for consideration may include both terrestrial and aquatic/marine organisms depending on access and the particular isotopes of interest. Although it is not within the scope of the present paper to provide a comprehensive description of the various environmental and metabolic pathways that may influence signature uptake, it is worth noting that environmental fates and chemistries will significantly impact the chemical species, concentrations, and biological availability of chemical as well as radiological and nuclear signatures of interest. Substantial transfer of radionuclides and other contaminants into animal matrices (*e.g.*, food products) may occur based on the particular features of the release or the contaminated system, but proposed sentinel species and sampling matrices should be carefully deliberated in light of the above.

Marine and aquatic animals. Numerous marine animals are known to accumulate radionuclides, and many of these, including bivalves (clams, scallops, and mussels), crabs, shrimp, and other coastal inhabitants, have been used for environmental monitoring. Aquatic animal accumulators include crayfish and bony fishes. Several long term studies have evaluated Cs-137 concentrations in Baltic Sea fauna resulting from the Chernobyl accident.[163] Assessment of bioaccumulation and biomagnification in both fish and seals revealed considerable variability among species in terms of radioisotope retention, presumably because of differences in metabolism or trophic position. In addition, levels of Cs-137 in seal tissues were higher than would be predicted by the physical half-life of the radionuclide, indicating that recirculation from sediments and/or inputs from freshwater sources was likely occurring. Similarly, evaluations of zooplankton and mesopelagic fish in the Northwest Pacific Ocean following the Fukushima accident resulted in detection of Fukushima-derived Cs-134 and -137 (as well as Ag-110m in zooplankton) in the tissues of surveyed species, although offshore stirring and mixing of oceanic waters led to considerable heterogeneity in distribution of radionuclides and associated presence in biota.[164]

Terrestrial animals. This category includes vertebrates and invertebrates that inhabit both riparian (i.e., land associated with a water course) and terrestrial environments. Environmental or reclamation studies that evaluate ecosystem health based on animal systems use a typical suite of sentinel species which include snails, frogs, ducks, crabs, and bees, whereas studies more concerned with evaluating contamination of human food sources focus on species that represent entry points into agri-food chains. For the presently proposed application, the latter is likely to represent a more accessible source of sampling. Agricultural, free-ranging domesticated, and game animals can be exposed to IR resulting from nuclear and radiological incidents via multiple routes including inhalation and ingestion of contaminated plants, water, and soils. Three primary radionuclides, including radioiodine, radiocesium, and radiostrontium, are highly mobile in environmental matrices and readily transfer to animal tissues and products.[165] Larger species like ungulates consume up to 25% of their body weight daily in primary biomass such as grains, stems, and leaves that can retain radiostrontium and, to some extent, radioiodine for extended periods, thus body burdens can be appreciable depending on factors like, *e.g.*, general nutrient availability and ingestion of clean versus contaminated feed. Exposure to radiocesium also occurs through grazing activity that results in ingestion of contaminated soils. Numerous studies validate collection of milk, muscle tissue, and excreta as a means to evaluate exposure to specific radionuclides.[166]

Genetic damage, metabolic changes, enzymatic markers, and other molecular endpoints. A number of biomarkers that can serve as tools for identifying exposure events have been identified. Assays have been developed and validated for biomarkers including, among others, cytogenic changes, DNA damage, transcriptional changes, and oxidative stress repair pathway activation. Assessments of biota inhabiting the radiation-contaminated areas of Chernobyl and Fukushima have yielded equivocal evidence of genetic damage and increased mutational rates[155]; however, the scientific community continues to lack consensus regarding the long-term effects of chronic exposure on wildlife that inhabits those areas.[167] It is not clear that levels of radiation in the aforementioned sites are sufficient to induce DNA damage which will exceed biological repair capacity, nor that the standard linear dose-response paradigm, which maintains that DNA lesions will increase linearly with energy deposition, applies to doses below a certain threshold. Other markers may have greater utility for the applications proposed in the present thesis.

For example, studies of inhaled uranium exposure demonstrate that urine concentrations of β2-microglobulin serve as a good proxy for yellow-cake exposure.[168] Sensitivity of the assay and the time scale post-exposure that the organism would be able to detect the signal was reported to range from 0.001 to 5 Gy and minutes to years, respectively. In general, longer or higher exposures provide more detectable signatures.[169] Epigenetic markers have also been associated with exposure to radiation. Both laboratory and field studies demonstrate characteristic modifications, putatively to induce DNA stability, under conditions of low, chronic exposure to gamma radiation.[170] Epigenetic changes like histone modifications, DNA methylation, and non-coding RNAs can influence end-state gene products (e.g., proteins) without altering underlying DNA sequences. Moreover, said changes can persist across multiple generations, thus may be "conduits for environmental influence" on the genome as long as a given environmental change persists.[171] Transcriptomic changes are likewise sensitive indicators of low dose radiation exposure. Several studies have documented modifications in gene expression patterns, particularly related to immune responses and inflammatory pathways, following exposure to low doses of IR and provide evidence that transcriptomics analysis are useful in evaluating the effects of prolonged external exposures.[172,173] Other "-omics" approaches for evaluating the effects of exposure include proteomics and metabolomics. Recent studies have investigated, *e.g.*, post-translational modifications to proteins critical to modulating a number of important biochemical pathways and determined that gamma exposures as low as 0.1 Gy were sufficient to induce significant changes.[174]

Whereas interrogation of molecular endpoints represents a promising direction for evaluating exposure to radiation, research remains largely in the fundamental stages. Challenges associated with development of methods and refinement of analytical capabilities to identify points of coalescence across highly variable genetic backgrounds have hindered practical application of such approaches. More work is required to identify the specific endpoints that may be useful.

<u>Population- and Community-Level Changes</u>. Population- and community-level effects are also evident in areas contaminated by radiation. The relative abundance of different species in and around Chernobyl (where doses range from an estimated 0.01 to136 μSv/hr) appears to be influenced by variation in background radiation. Researchers found that mammals and birds showed the strongest negative relationship between abundance and background radiation levels as compared to dragonflies, butterflies, amphibians, and reptiles.[155] Similarly, numerous studies demonstrate the impacts, whether beneficial or deleterious, of modern war and military activities that result in exposure to radiation.[175] Such results suggest that relative abundance of select species is indicative of radiological and other types of contamination associated with nuclear activity. A non-trivial caveat is that studies like those cited above required (1) continual access to sites of interest and (2) longitudinal sampling to draw statistically robust conclusions. Certain endpoints (*e.g.*, genetic endpoints) could assist in drawing inferences from more limited collection efforts, but sample sizes resulting from a given effort would still need to be large enough to promote confidence in conclusions.

Humans

A number of potential endpoints for evaluating occupational exposure are provided in the associated overview article "Harnessing the Environment to Identify Nuclear Processes: Biologically-Mediated Approaches" and include direct measurements of radionuclides in biological samples, inference of exposure through analysis of serum enzyme levels, genomic and proteomic changes, and community restructuring of the skin and oral microbiomes. Detail regarding signatures for which such endpoints are known to be relevant is provided therein. Additionally, many of the approaches delineated in the "Native and Domesticated Animals" section, above, and select approaches from the "Biological Materials" section, below, will apply.

Biological Materials

Certain species act as unique collection systems by incorporating environmental contaminants into anatomical structures, such as shells or exoskeletons. Marine and freshwater invertebrates, including benthic (sediment dwelling) invertebrates, are often used as biomonitors to assess population-level effects of anthropogenic pollution, thus have been the subject of considerable study evaluating accumulation and incorporation of contaminants into different body tissues. For example, the mussel *Mytilus edulis* has been widely used as a sentinel organism for monitoring pollution in aquatic habitats, and laboratory studies have demonstrated its ability to concentration radionuclides such as Pu, Am, and Sr into shell material.[176] Studies of terrestrial invertebrates like the gastropod *Helix aspersa* have also demonstrated that the shell is a primary depot for certain contaminants like heavy metals.[177,178] Although information on trophic transfer (i.e., up the food chain) of radionuclides is relatively limited, some studies indicate that biomagnification of radionuclides and heavy metals occurs during transfer to predatory species (*e.g., Babylonia formosae habei*), likely due to high assimilation efficiencies of foodstuffs.[179] Given their demonstrated efficiency as bioconcentrators, macroinvertebrate exoskeletons could offer viable alternatives to traditional collection systems. Moreover, because individual shell layers are developed during specific stages of life, it may be possible to infer the time range during which exposure occurred. New techniques in mass spectrometry (*e.g.*, multi-isotope imaging mass spectrometry) show promise in terms of characterizing isotopic ratios in biological materials at the subcellular level, thus can putatively support analysis of the materials described above.[180]

Calcified tissues such as exfoliated deciduous teeth181 and walrus tusks[182] are also known to be exceptional lifetime integrating dosimeters through the application of electron paramagnetic resonance (EPR). With regard to the former, samples retained from root canals, denture fittings, wisdom teeth extraction, and so on, can be obtained with the assistance of dental surgeons and then submitted to an EPR lab for dose reconstruction. High precision and accuracy can be obtained using detailed protocols and techniques[183] although much of the process is also amenable to automation184. When EPR is used in combination with alanine dosimetry, detection limits can be as low as 10s of millisievert.[185] Based on differential attenuation of medical x-rays and external gamma as they penetrate teeth, the contribution from diagnostic exposures is easily distinguishable by measuring the dose-depth profile.[186]

Thermoluminescence (TL) and optically stimulated luminescence (OSL) also have been used to characterize the above and comparable materials. Although TL and OSL are more commonly associated with personnel dosimetry (e.g., radiation worker badges), use of OSL via distributed dosimeter arrays has demonstrated application for reconstruction of historical weapons grade plutonium locations and distributions.187 Similarly, TL and OSL have demonstrated ability to establish dose-depth profiles sufficient for reconstruction of historical radiation fields for Am-241 in bricks[188] and retrospective assay of historical uranium enrichment levels in bricks and other ubiquitous building materials, even when the nuclear material no longer exists.[189] Detection levels approaching natural background have been demonstrated for personal items commonly found in the public,[190] although further research is needed to validate findings. It is reasonable to suppose that the same approaches could be extended to biologically-derived materials.

Ecological Networks

Mycorrhizosphere. Mycorrhizae ("myco" = fungus + "rhizo" = root) are widespread networks of symbiotic water, nutrient, and information exchange between plants and soil fungi, and approximately 80% of terrestrial plants form such mycorrhizal associations. The filaments or "mycelium" of fungi thread through the root systems of plants, receiving carbohydrates and returning water and minerals. In addition to the exchanges between plant and fungal partners, plants can distribute resources to other plants of the same or different species in a community through shared, interconnecting fungi.[191] Furthermore, plants can direct chemical signals of distress to neighboring plants through shared fungal networks, communicating specific threats such as disease or grazing.[192]

A single plant can link with multiple species of fungi and vice versa. The aggregation of unit connections between plant nodes and fungal relays form vast underground systems that have been dubbed "myconets" or "the wood-wide web".[193] Myconets both physically and functionally resemble human information networks, and so efficient is their organization and distribution that network engineers examine myconets to inform their own designs.[194] Due to the interconnectivity of fungi, disturbances to any part of an ecosystem are translated into intelligible signals distributed across the local myconet.[192-194,195]

The influx of the unique radiochemistries and energy produced by fissile materials or nuclear processes into an ecosystem can be relayed across a myconet. Fungi are also known to bioaccumulate heavy metals and radionuclides, which may lead to establishing "mycological fingerprints" as biorecognition elements for isotopes of interest. Myconet-based detection offers the potential to leverage sensing capacities of multiple plant and fungal species across an ecosystem for use in broad surveillance scenarios. Distress signals can be transmitted underground through chemical communications or through the air over significant distance by volatile chemicals, pollen, or spores. Myconets can be monitored through chemical analysis of root samples or downwind air sampling of volatile chemicals. While myconets possesses great potential to capture and transmit information from multiple biological sources, the science to receive and process biochemical signals associated with myconets is still nascent. Further investigation of these ecological networks is necessary to engage this resource as a viable recognition element in sensing technology.

Conclusion

The biological world offers a wealth of possibilities for development of environmental monitoring systems that are uniquely capable for the identification and characterization of nuclear activity. The previously described systems can provide, alone or in concert, clear indication of the nature and extent of contaminating events through careful and systematic interrogation. Techniques for leveraging the information they provide have become increasingly refined as have computational approaches that help to make sense of the manifold layers of information likely to result, especially where multiple environmental stressors may be present. Although several of the concepts delineated here can be adapted for immediate use, others will require additional research to develop fully mature capabilities for incorporation into the nuclear monitoring toolkit.

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U.S. Army Nuclear Disablement Team trains at uranium facilities

Mr. Walter T. Ham IV,

20th CBRNE Command Public Affairs

Figure 1. Nuclear Disablement Team 1 "Manhattan" Soldiers pose in front of yellowcake slurry vats following training at Nichols Ranch In-situ Recovery Plant near Casper Wyoming. During Operation Pay Dirt, the Aberdeen Proving Ground, Maryland-based Nuclear Disablement Team 1 trained at the White Mesa uranium mill in Utah and the Nichols Ranch in-situ recovery mine and plant north of Casper, Wyoming, April 4 - 8. U.S. Army photo by Maj. Mark S. Quint.

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Operation Pay Dirt

During Operation Pay Dirt, the Aberdeen Proving Ground, Maryland-based Nuclear Disablement Team 1 trained at the White Mesa uranium mill in Utah and the Nichols Ranch in-situ recovery mine and plant north of Casper, Wyoming, April 4 - 8.

Maj. Mark S. Quint, the team leader for NDT 1, said Operation Pay Dirt provided a great training opportunity for his one-of-a-kind team.

"The NDT has focused primarily on nuclear infrastructure associated with the enrichment process and all of the following steps necessary to develop a nuclear weapons program," said Quint. "Our partnership with this industrial scale manufacturer provides an incredibly valuable training venue as their facilities are analogous to the facilities our adversaries abroad possess."

Army NDTs directly contribute to the nation's strategic deterrence by staying ready to exploit and disable nuclear and radiological Weapons of Mass Destruction infrastructure and components to deny near-term capability to adversaries. The specialized teams also facilitate follow-on WMD elimination operations.

The U.S. Army's three Nuclear Disablement Teams — NDT 1 "Manhattan," NDT 2 "Iron Maiden" and NDT 3 "Vandals" — are part of the Aberdeen Proving Ground, Maryland-headquartered 20th Chemical, Biological, Radiological, Nuclear, Explosives (CBRNE) Command, the U.S. Department of Defense's premier all hazards headquarters.

Figure 2. Maj. Jonathan W. Schwarz and Capt. Derek D. Whipkey take spectroscopy of U3O8 precipitation tanks at Nichols Ranch in-situ recovery plant near Casper, Wyoming. During Operation Pay Dirt, the Aberdeen Proving Ground, Maryland-based Nuclear Disablement Team 1 trained at the White Mesa uranium mill in Utah and the Nichols Ranch in-situ recovery mine and plant north of Casper, Wyoming, April 4 - 8. U.S. Army photo by Maj. Mark S. Quint.

“NDT operations are inherently dependent on our interagency partnerships. This training allows the NDTs to more efficiently exploit similar infrastructure to inform our joint partners on WMD capacity of adversary states,” said Quint. “Furthermore, in operations with allied nations, our team can help maximize the efficiency of limited CBRNE forces, by recommending to the theater CBRNE commander which type of units can exploit different facilities.”

Quint said NDT 1 was able to leverage the vast experience of the staff at Energy Fuels during Operation Pay Dirt.

“The highlight of the training was our direct interaction with the exceptionally knowledgeable staff,” said Quint. “The passion that those staff members exude is evident in their facilities. Also, it is invaluable for NDT members to train on industrial scale infrastructure, and both Energy Fuels sites offered that.”

Figure 3. Maj. Mark S. Quint (left) and a member of the White Mesa staff examine the process control room at the uranium mill. During Operation Pay Dirt, Soldiers from the Aberdeen Proving Ground, Maryland-based Nuclear Disablement Team 1 trained at the White Mesa uranium mill in Utah and the Nichols Ranch in-situ recovery mine and plant north of Casper, Wyoming, April 4 - 8. U.S. Army photo by Col. John P. Kunstbeck

Quint said he believes the partnership with Energy Fuels will continue in the future and will contribute to the readiness of the U.S. Army’s Nuclear Disablement Teams.

“Based on their generosity, patriotism and culture of openness, I believe this partnership with Energy Fuels will continue in perpetuity. We’re excited to continue to send our forces to their facilities to gain a world class understanding of the uranium mining and milling process,” said Quint, a 14-year U.S. Army veteran from Paulsboro, New Jersey.

Quint served as a field artilleryman before becoming a U.S. Army Nuclear and Countering Weapons of Mass Destruction (FA 52) officer.

“Readiness is at the core of the NDT mission. Our adversaries must continue to understand that the Nuclear Disablement Team remains the U.S. Army’s premier resource for technical exploitation of nuclear infrastructure worldwide,” said Quint. “Energy Fuels is one of our partners in industry, academia and government that help fulfill our unique yet critical mission. We are grateful to them and many others for their ongoing commitment to our readiness.”

Figure 4. Sgt. Joshua M. Kamami examines a bank of mixer settlers during rare earth element recovery operations at White Mesa Uranium Mill near Casper, Wyoming. During Operation Pay Dirt, the Aberdeen Proving Ground, Maryland-based Nuclear Disablement Team 1 trained at the White Mesa uranium mill in Utah and the Nichols Ranch in-situ recovery mine and plant north of Casper, Wyoming, April 4 - 8. U.S. Army photo by Maj. Mark S. Quint.

Curtis H. Moore, the vice president for marketing and corporate development at Energy Fuels, said his team was impressed by the wide variety of instruments the Nuclear Disablement Team employed during the training.

“They had a broad range of equipment that they were able to use effectively to identify and characterize the materials and potential hazards present in an operating uranium mill,” said Moore who has worked for the Lakewood, Colorado-based corporation for nearly 15 years.

Moore said Energy Fuels is the largest U.S. uranium producer and White Mesa Mill is the only conventional uranium and vanadium mill in the nation.

According to Moore, Energy Fuels would welcome the opportunity to host NDTs at their facilities again in the future.

“It was a genuine pleasure to host the U.S. Army Nuclear Disablement Team at our facility. We always appreciate the opportunity to discuss our operations, from our commitment to environmental responsibility to our ability to domestically produce many critical materials,” said Moore. “The Nuclear Disablement Team’s insightful questions and dedication to their mission was a unique experience for us. We’d be happy to host them, and others in the U.S. Army, again in the future.”

Targeting Al Shifa: Explaining an Intelligence Failure

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Abstract

This paper examines the intelligence failure surrounding the bombing of the Al Shifa factory on August 20, 1998. The factory was bombed in retaliation for the August 1998 attacks on the US Embassies in Kenya and Tanzania by Al Qaeda. At the time, it was thought that the Al Shifa factory was producing VX for the Al Qaeda network. However, subsequent analysis has shown that it is extremely unlikely that Al Shifa was involved in VX production, nor is it probable that Al Shifa was linked to Al Qaeda. In a prelude to the Iraq WMD fiasco, some of the same intelligence pathologies--to include politicization, an inability to examine negative evidence, and poor collection and analytical tradecraft--were prevalent in the Al Shifa example. This paper examines those intelligence failures in depth.

On August 20, 1998, US warships launched 13 Tomahawk missiles at the Al Shifa factory in Sudan, completely destroying the plant. The attack was a response to the bombing by Al Qaeda of United States (US) embassies in Kenya and Tanzania two weeks prior. The US intelligence community assessed that the plant was connected both to Al Qaeda and the production of highly lethal VX. If true, the Al Shifa plant would have posed a significant threat to US interests.

However, all evidence indicates that Al Shifa was not connected to Al Qaeda, nor was it involved in the production of chemical weapons. Before the advent of drone targeting, bombing another country was considered an act of war and implemented only as a response to confirmed intelligence and a large threat to national security. In this case, the intelligence and its use by policymakers was flawed, creating the condition that warranted the use of Tomahawk missiles.

How did this failure happen? In a prelude to the Iraq weapons of mass destruction (WMD) intelligence failure, a combination of inadequate collection, analytical traps, politicization, and an inability to communicate nuance to policymakers led to the erroneous targeting of Al Shifa. Ironically, if the Al Shifa failure had been analyzed more thoroughly, it is possible that the Iraq WMD failure might have been entirely avoided.

Rohin Sharma is currently the senior Middle East analyst at the Defense Threat Reduction Agency (DTRA). In this capacity, he provides detailed threat assessments to the senior DTRA leadership, with specific emphasis on trends in Chinese nuclear modernization. In addition, Rohin serves as an adjunct in the Security Studies program at Georgetown University, where he teaches a course that analyzes intelligence failure.

Previously he served as the senior Middle East/Terrorism Analyst at the US Army. In this capacity, he is responsible for briefing the senior Army leadership (including the Chief of Staff) on all issues relevant to current operations in the CENTCOM region. Prior to working at the Army G2, Rohin worked at the Defense Threat Reduction Agency. At DTRA, he was responsible for analyzing threats and assessing vulnerabilities related to Weapons of Mass Destruction and nuclear proliferation. Rohin also worked as an analyst with the Department of Defense, specifically focused on the IED problem set. In this capacity, he integrated academia, industry, and the intelligence community in defeating this threat. He was recognized as a subject matter expert in his field and briefed at numerous conferences, meetings, and congressional forums.

Rohin spent seven years on active duty in the US Army as an intelligence officer. While on active duty, Rohin deployed to OPERATION IRAQI FREEDOM as a Battalion S–2 with the 101st Airborne Division. In addition, he was a J2 planner during OPERATION ENDURING FREEDOM from 2003–2004. Rohin also served as a ground surveillance platoon leader in the Republic of Korea in 2001. He holds a MA in Security Studies from Georgetown University and a BA from Johns Hopkins University.

This paper will begin with an overview of the decision making process that lead to the strike on Al Shifa. It will then analyze the intelligence used to nominate Al Shifa as a potential target. Focus will then turn to how politicization played a role in the Al Shifa attack. Next, the paper will examine specific and analytical failures perpetrated by the intelligence community outside the policy/political interface. The paper will conclude with rebuttal arguments put forth by Clinton administration officials that were involved in the decision to strike Al Shifa.

The Decision to Bomb

Initial Collection

The original connection between Al Shifa and Osama Bin Laden came in 1995 when reporting indicated that Bin Laden, a resident of Sudan at the time, had contacted the Sudanese government for assistance with chemical weapons. In 1997, an informant "reported that two sites in Khartoum might be involved in chemical weapons production."[1] The same informant, whose reliability was unknown, mentioned that Al Shifa might also be producing chemical weapons due to "high fences and stringent security."

Based on this initial reporting, the Central Intelligence Agency (CIA) sent an agent in December 1997 to collect a soil sample from the plant. While the sample was initially reported as coming from the grounds of the facility, the soil was actually taken 20 meters outside the plant. When the soil was examined by various US labs, EMPTA was found at "2.5 times that which would be regarded as a mere trace; presumably, exculpatory evidence to explain its presence was not discovered."[2] EMPTA, O-Ethyl Methylphosphonothioic Acid, is a known precursor for VX nerve agent, one of the deadliest chemical weapons at the time. The presence of EMPTA, which had some, but not widespread commercial use, (discussed in more detail below), elevated Al Shifa as a threat and potential target.

Further reporting indicated a possible linkage between Bin Laden and Al Shifa, "including indirect financial connections through the Military Industrial Corporation, a government controlled company."[3] In addition, Bin Laden's previous relationship with the Sudanese government may have led analysts to draw erroneous connections between Al Qaeda and the Al Shifa plant. A July 24, 1998, a CIA report highlighted these conclusions but also recommended "more soil samples and additional satellite photography." It also noted that there were no longer signs of heavy security around the facility.[4]

Retaliating for the Embassy Attacks

On August 8, 1998, Al Qaeda simultaneously struck the US embassy compounds in Nairobi, Kenya, and Dar-es Salaam, Tanzania. US intelligence and law enforcement agencies quickly determined that Bin Laden was behind the strike (in a poorly articulated phrase that he would repeat in the days leading to the Iraq War, CIA Director George Tenet pronounced it a "slam dunk case"). The National Security Council immediately developed a "small group" consisting of Secretary of Defense William Cohen, National Security Advisor Sandy Berger, Secretary of State Madeline Albright, Director Tenet, and National Security Council (NSC) Counterterrorism Director Richard Clarke to evaluate intelligence and determine retaliatory measures. The group was purposefully kept small in order to prevent leaks to the media.

The small group tasked the Department of Defense and the CIA Counterterrorism Center with developing a list of targets for retaliatory strikes, with Al Shifa making the list. This list was first briefed to President Clinton on August 12. However, the CIA "received new intelligence show{ing} that Bin Laden and his key lieutenants would be meeting on August 20th in Khost, Afghanistan".[5] This meeting provided a lucrative target and could easily be justified, given the Al Qaeda attacks in Kenya and Tanzania.

However, for reasons that remain unclear, the dubious strike on Al Shifa would be linked to justified retaliation in Khost. Richard Clarke explained that "Bin Laden had shown global reach by attacking American embassies simultaneously in two countries"[6] and, therefore, the US had to strike in two countries. According to chemical weapons expert Johnathan Tucker, it was President Clinton who made the decision to strike two targets simultaneously. The decision to strike two targets appeared to have been an attempt to show "strength" regardless of the actual national security threat.

Regardless, the operation to strike al Shifa continued. On August 19th, final recommendations were made for targeting the Khost site, the Al Shifa plant, and another site in Khartoum, Sudan. Notes taken at the meeting indicate that Tenet mentioned that there were "gaps linking Al Shifa to Bin Laden, however, the CIA was "working to close the intelligence gaps on this target"[7] It is not clear if Tenet meant that the gaps were to be closed before the attack or as part of a post attack justification.

Aftermath

Following the attack, US officials explained their rationale for targeting the plant. President Clinton said "the plant was destroyed because it was a chemical weapons related facility,"[8] implying that the production of chemical weapons occurred there. Hugh Shelton, Chairman of the Joint Chiefs of Staff, took the rationale a step further, stating that "the intelligence community is confident that this facility is involved in the production of chemical weapons agents including precursor chemicals for the deadly V series of nerve agents like, for example, VX."[9] Secretary of Defense Cohen appeared to backpedal slightly when he stated that the facility "produced precursor [not complete product] chemicals that would allow the production of VX nerve agents."[10]

However, further scrutiny and media reports would undermine the rationale for the targeting of Al Shifa. The designer of the plant, an American pharmaceutical consultant, insisted that that it did not have equipment to construct a nerve agent. A British engineer, Thomas Carnaffin, who worked as a technical manager during the plant's construction between 1992 and 1996, stated that the plant "was neither heavily guarded nor secret, and that he never observed evidence of the production of an ingredient needed for nerve gas."[11] Dino Romanatti, the plant's Italian supplier, said that "he had full access to the facility during visits in February and May 1998, and saw neither equipment nor space necessary for CW production." Romanatti described plant resources as very limited: "the availability of tools in the factory was close to zero. You couldn't get a piece of steel, a screw, a saw. To imagine a plant that makes chemical weapons is absolutely incredible."[12]

The Sudanese government vehemently denied that chemical weapons were being produced or that there was a connection to Al Qaeda. Sudanese officials "arrived at Al Shifa while the plant was still burning, which presumably would have been personally hazardous if the plant had been involved in CW production."[13] The Sudanese went even further, calling for an international inspection of the Al Shifa site-- something that was denied by the Clinton Administration and, to date, still has not been conducted.

Finally, despite what was announced by the Clinton administration, the plant was not heavily guarded, contradicting a key piece of intelligence that claimed there was clandestine activity occurring at Al Shifa. Corroborating the comments of Carnaffin, journalists who visited the ruins of the plant reported that "it had not been under heavy security prior to the attack."[14] Further, the "German Ambassador to the Sudan, Werner Daum, reported to Bonn... that the plant was neither secret nor disguised. The report said Shifa could 'in no way be described as a chemical plant,'[15] but was instead 'Sudan's largest pharmaceutical plant.' Bishop HH Brookings from the African Methodist Episcopal Church in Nashville, Tennessee, was able to freely tour the facility days before the attack, and noticed no signs of increased security.[16]

<u>Dubious Intelligence</u>

The case for targeting Al Shifa was based primarily on two sources of intelligence: a soil sample that had high traces of EMPTA—a precursor for VX, and assessed financial connections between the Al Shifa plant and Osama Bin Laden.

Soil Samples

The "smoking gun" for targeting Al Shifa was the soil sample collection which contained a high concentration of EMPTA. The soil sample was taken 20 meters from the plant (and not on the facility as originally reported), and had a concentration level 2.5x than what was found naturally.[17] Further damning was the fact that EMPTA was used specifically in the Iraq VX program, indicating a connection between Iraq and the plant (although no connection to Al Qaeda). Finally, while EMPTA does have some commercial use, it does not have any applications in the pharmaceutical industry, a key piece of intelligence given that this was the reported purpose of the Al Shifa facility.

However, there are problems with automatically assuming a connection to VX based on the EMPTA soil sample. First, the sample was not taken from the grounds of the Al Shifa facility. Even if VX was being produced, it is not clear how the precursor material could have landed so far away. Secondly, it is important to note that the EMPTA is a precursor material, and not the final product of VX. Clinton administration officials were clear that that plant produced VX, yet only remnants of the precursor material were found (a far cry from actual production).

Moreover, EMPTA has other commercial applications aside from the production of VX. EMPTA is listed as a schedule 2 chemical, making it a dual use chemical. A spokesman for the Organization for the Prohibition of Chemical Weapons (OPCW) stated that EMPTA could have "legitimate commercial purposes such as fungicide production." In addition, "Chemical Weapons experts have since suggest that Fonophos, an organphosphate insecticide, had been used quite often throughout Africa and could have been misinterpreted for EMPTA."[18]

Finally, the use of soil samples to detect clandestine chemical weapons programs is not a reliable technique. Its true value usually occurs after an incident, such as the 1988 Iraqi attack against the Kurds in Halabja, or the August 2013 gassing in Damascus by the Syrian regime. Sampling rarely works as a standalone collection method with chemical weapons, and its value is further diminished when collecting precursor material like EMPTA vice the final chemical weapons product.

None of these issues were shared with senior policymakers prior to the Al Shifa strike. It is also likely that all further intelligence was analyzed with the intention of confirming the soil sample as opposed to disputing it.

Linking Bin Laden to Al Shifa

Perhaps the most dubious intelligence was the attempt to establish a connection between Bin Laden and the Al Shifa plant. Following the strike, an unnamed intelligence official stated that "we know that Bin Ladin has made financial contributions to the Sudanese military complex. That's a distinct entity of which we believe the Shifa pharmaceutical facility is a part."[19] Intelligence analysts were also aware that Bin Laden had spent time in Sudan at the host of its government, although he had been expelled before the 1998 attack. US intelligence agencies were also aware that Al Qaeda was attempting to acquire chemical weapon capability, although the extent of their acquisition was unknown at the time. Finally, US intelligence was aware that there were connections between officials at Al Shifa and Iraqi chemical weapons experts, with the EMPTA precursor, used extensively in the Iraqi program, furthering the link between Iraq and Al Shifa.

However, this evidence does not withstand scrutiny. Even if there had been connections between Al Shifa and Iraq, it would not necessarily translate into a connection to Al Qaeda (a point that was litigated extensively prior to the Iraq War). Furthermore, unbeknownst to the CIA, ownership of the plant had changed hands six months prior to the Al Shifa attack, further diluting the Iraqi connection.[20] Finally, the connections between Bin Laden and Sudan at this time were tenuous, largely due to his expulsion by the Sudanese government. While there could have conceivably been some links, it is difficult to conceive that the Sudanese government and Bin Laden would have had such a cooperative relationship given his recent expulsion.

Connecting Bin Laden to Al Shifa required certain mental gymnastics. It appears that analysts and policymakers suffered from an "Iraq is bad, Iraq is involved in VX production (or so the US thought at the time), Bin Laden is bad, therefore Bin Laden is involved in VX" mentality. The connections tying Al Qaeda to Al Shifa were almost non-existent from an objective point. However, in the backdrop of the embassy bombings, like the World Trade Center attacks three years later, tenuous connections were magnified with little alternative evaluations.

Intelligence Politicization

How did this failure occur? While there are several factors including substandard intelligence collection and analytical tradecraft, the overwhelming reason was that the intelligence was framed in such a way as to fit policymakers' desires. Congruently, intelligence analysts failed to communicate nuances and alternative analyses to policymakers, thus providing policymakers with a lot more surety than was warranted.

Before discussing what politicization is, it is important to explain what it is not. First, several people accused Clinton of using the Al Shifa strike to distract from the ongoing inquiry regarding the Monica Lewinsky affair, referred to as a "Wag the Dog" scenario. There is no evidence that Clinton launched the strike to distract from the affair, nor is there any indication that intelligence was "cooked" in order to cover his domestic troubles.

Secondly, there is a false assertion that politicization only occurs when policymakers either alter intelligence reports or bully intelligence analysts into accepting predetermined conclusions. The 2004 Senate report on pre-war Iraqi intelligence found no evidence of this type of politicization ahead of the Iraq WMD failure. In fact, this type of overt action is exceedingly rare, and there is no evidence that this occurred in the Al Shifa case.

Politicization occurs, however, in more subtle ways, even being so subtle that a policymaker may not even realize he or she is engaging in it. "Subtle politicization" happens when there is an inordinate requirement on an intelligence organization, originating from a policymaker that forces the intelligence organization to act in ways counter to best practices.[21] This is different than more egregious levels of politicization, where the intelligence community is forced to "cook the books" for a policymaker, or fears negative career retribution for not toeing the policymakers line.

In the Al Shifa case, it is clear that the request for striking two targets was the subtle politicization that caused the Al Shifa intelligence failure. Reports indicated the desire to strike two targets occurred because Al Qaeda had struck two separate countries with the embassy bombings.[22] This logic was not the result of any analysis on the Al Qaeda network, nor did it come from an evaluation of threats facing national security. It appeared to emerge from a need to publicly "demonstrate" US resolve-- a dubious rationale for striking a separate country in the pre 9/11 era.

Regardless, the political decision to strike two targets had several impacts that negatively affected the intelligence assessment on Al Shifa. First, it robbed the intelligence community of time to collect more information on the Al Shifa plant. According to a July 24, 1998, CIA report (issued two weeks before the embassy bombings) there was a requirement for "more soil samples and additional satellite photographs,"[23] to confirm the presence of VX at Al Shifa. Obviously, the compressed timeline of striking two targets by August 20th prevented any attempt for additional collection activity against the facility.

Secondly, it proved to be a forcing function for bad intelligence to bubble to the top. Policymakers were actively looking for a target under time pressure, forcing the intelligence community to provide targets based on dubious intelligence. Without the requirement for immediate action, it is likely that there would have been more questions on both the EMPTA evidence and the connections between Al Shifa and the Al Qaeda network. Indeed, after the strike, analysis from the broader State Department Bureau of Intelligence and Research determined that the intelligence used to target Al Shifa was shoddy.

Furthermore, the requirement from the Clinton Administration for two targets, combined with the artificial time constraint, prevented an analysis of the evidence from the larger intelligence community, a typical practice for controversial assessments. Ironically, the intelligence for Al Shifa came from the CIA Counterterrorist Center and not the WMD experts at the Weapons Intelligence, Nonproliferation, and Arms Control (WINPAC) at CIA, who were notified of the Al Shifa strike on the day before it was carried out.[24] Nor was the State Department Intelligence and Research Bureau (INR) consulted prior to the attack. Both WINPAC and INR had serious concerns about the intelligence on Al Shifa; however, the compressed timeline prevented incorporation of these agencies into the process.[25]

Finally, Sandy Berger's assertions during the debate likely skewed the intelligence. Berger is quoted as saying "what if we do not hit [Al Shifa] and then after an attack, nerve gas is released in the New York City subway? What will we say then?"[26] Obviously, a quote like this is not based on intelligence or an objective view of national security threats, but political perception. This likely colored the views of the policymakers and made the attack more likely.

Communicating with Policymakers

A Closed Process:

In his book *Red Team*, Michael Zenko argued that an alternative analysis should have been completed on the intelligence related to the Al Shifa plant. A simple Team A/Team B approach, even conducted under a tight time constraint, would have shown the hollowness of the intelligence related to Al Shifa and may have prevented the attack.

However, alternative analyses would still have to be filtered through the person or agency actually communicating it to the policymakers. Due to the closed nature of the decision-making surrounding the Al Shifa plant, all intelligence was filtered through Tenet, the CIA director. If there had been alternative analyses, it was his job to communicate nuances of the Al Shifa intelligence to policymakers.

Tenet may have briefed some nuances to the policymakers, warning that the "link between Bin Laden and the factory could be drawn only indirectly and by inference."[27] However, it was apparent the policymakers did not hear any of the nuances and disclaimers. Sandy Berger, the National Security Advisor reported that "the director was very clear in the plants association with Chemical Weapons."[28] Richard Clark, the senior NSC director, went a step further stating that "the US government is sure that the Iraqi nerve gas experts actually produced a powdered VX like substance at the plant that when mixed with bleach and water would become fully active VX."[29] Secretary of Defense Cohen argued:

> *That the plant itself had been constructed under extraordinary security measures, that the plant had been funded, in part, by the so-called military industrial corporation, that bin Laden had been living there, that he had in fact money that he had put into this military industrial corporation, that the owner of the plant had traveled to Baghdad to meet with the father of the VX program, and that the CIA had found traces of EMTA nearby the facility itself. According to all the intelligence, there was no other known use for EMTA at that time other than as a precursor to VX.*[30]

Based on what the policymakers understood of the intelligence, it is clear that nuances and caveats of intelligence were not clearly articulated. While no exact transcripts of meetings are available (in the unclassified public domain), the intelligence community, represented solely by Director Tenet, should have communicated the following much more clearly:

- EMPTA residue at the Al Shifa plant was not a definitive indicator of the presence of chemical weapons. As stated earlier, the EMPTA may have had other commercial purposes and its connection to VX was far from definitive.
- There is a vast difference between precursor material and finished product. From the above statements, it is clear that the policymakers believed that production of VX from EMPTA was an easier process than it could be.
- in Laden financial connections to Sudan were limited at best. Tenet may have communicated the tenuous financial connections between Sudan and Bin Laden, but it is apparent that policymakers were not receptive to this nuance.
- There was no direct connection between Bin Laden and Iraq: Secretary of Defense Cohen was clear that the connections between Iraq and Al Shifa were critical factors in the decision to attack. However, there was little intelligence connecting Bin Laden to Iraq and none connecting Iraq to the August 7th embassy attacks.
- Al Shifa did not have extraordinary security measures: according to a July 24, 1998, intelligence report by the CIA, it was noted that there no longer signs of heavy security around Al Shifa.[31] It is unclear if Tenet had been briefed on this or if he communicated it to policymakers. Secretary Cohen, however, believed the extraordinary security measures around Al Shifa was evidence of a clandestine weapons program.

Intelligence and Policy:

Early in their career, intelligence officers are warned that they do not "do policy"--that they inform decision makers but do not advocate a particular course of action. Sherman Kent believed there should be a "red line dividing policymakers and policy...this red line ensured that intelligence officers maintained credibility because they could not be accused of slanting evidence " to pursue a certain course of action. In theory, this dividing line allows intelligence to be insulated from politics and media, allowing for a more fact-based assessment.

In practice, however, this "red line" can absolve intelligence analysts from the responsibilities of intelligence failure. An intelligence official can simply claim, "I warned the policy maker" and could wash his hands of the issue. Furthermore, the "staying out of the policy realm" can prevent an intelligence official from imparting his or her true subject matter expertise for fear of crossing the line into advocacy.

Tenet was often accused of crossing the line into advocacy; however, in the Al Shifa case, it appears that he was too hesitant to bring in counter-factual claims, or at least providing a more detailed, broader intelligence picture. As the senior subject matter expert in the room, he should have provided the following objections:

1. Need for Simultaneous Strikes: As the CIA director, Tenet was obligated to recommend a strike against the Bin Laden camp in Khowst. However, he was also under the obligation to ask questions about the need to strike two targets simultaneously, given that there was no linkage between Al Shifa and Khowst. As stated earlier, the connection between the two facilities was the primary driver for targeting Al Shifa. From the policymakers' comments (Berger, Cohen, Clarke), it is apparent that he never brought forth this issue.

2. Requirement for More Collection: According to a July 24th report, the CIA recommended future collection against the Al Shifa target, including satellite images and additional soil samples. As the senior intelligence professional in the room, Tenet had an obligation to convey these issues to senior decision-makers. In addition, he owed policymakers an assessment on the assets and time necessary to confirm the presence of VX.

3. EMPTA as Merely a Precursor: The process from going from precursor to actual weaponization is quite intensive and maybe beyond the capability of non-state organization to achieve. While the presence of EMPTA was worthy of further collection, its connection to actual VX production and that it turn being a threat to the US was not clear at the time.

4. Overall Justification: If in fact, VX or other illicit chemical weapons were being produced, it is not 100% clear whether they would have posed an imminent threat to the US or its allies. The chemical would still need to be stored, transported and disseminated to be used as an effective weapon. Furthermore, even if VX was being produced, it would be hard to conceive that it could have been more of a threat on August 20th vice several weeks afterward, when more collection assets could have been dedicated to the facility.

Additionally, if Tenet had given a solid recommendation, it would have allowed policymakers to "bracket" the problem, providing them a better understanding of the threat. For example, if Tenet had proposed that the intelligence was so dire that missile strike was required immediately, then this would have communicated to the policymakers how ominous the threat was. However, if he recommended further collection and a "wait and see" approach, this would have signaled to policymakers that the EMPTA link to VX and the connections to Bin Laden were not as dire.

<u>Intelligence Community Failures</u>

While the majority of the blame for the Al Shifa failure lies with the policy-intelligence community interactions, the intelligence community in of itself should not be absolved from blame.

Collection Failures

From target identification to time of attack, the CIA had more than one year to collect on Al Shifa. During this time, they did not answer requirements that, if it was believed that VX was being produced, should have been a higher priority. Critical requirements that should have been answered, regardless of time constraints are the following:

1. Security around the facility: As stated earlier, intelligence gathered from very simple collection methods (either on the ground surveillance or overhead imagery) could have confirmed that there was no advanced security around Al Shifa. According to several of the policymakers, including Secretary of Defense Cohen, the presence of security around a "clandestine facility" was important in the decision to attack the facility. On the ground monitoring of the plant, or use of overhead imagery, could have confirmed that the plant was not under heavy security.

2. Presence of chemical weapons specific equipment: If in fact precursor material was being refined into VX, then advanced equipment (gas masks, specialized containers, personal protective gear) would have been visible to outsiders. While collecting Human Intelligence (HUMINT) from the plant would have been difficult due to the CIA's evacuation of Sudan several year earlier, there were

numerous guests given access to facility. One week prior to the attack, Bishop HH. Brookings of the African Methodist Episcopal Church in Nashville was given a complete tour of the Al Shifa facility, where he had ready access to the entire factory. The British Ambassador to Sudan had also been given access, as did the nonprofit group Sudanese Children.[32] If their members had been given access to the facility, it should have been possible for a CIA asset to gain access as well.

3. Ownership of Al Shifa: Another key collection omission was the intelligence community lack of awareness of the ownership of the Al Shifa. Much of the analysis was predicated on the belief that Al Shifa was owned by the Sudanese Military Complex who could, however circuitously, be linked to Bin Laden. However, the Al Shifa plant had been sold to Salah Idris, a local Sudanese, six months prior to the strike. The CIA would later claim that Idris was tied to Egyptian Islamic Jihad, however, this link occurred after the attack, and appeared to be an attempt to make a nebulous connection after the fact. The fact that the US intelligence community was not aware of a simple ownership transfer while the facility was being monitored for producing VX is a significant collection failure and a question that has never fully been answered.

As mentioned earlier, the political demands to identify a second target affected the ability of the intelligence community to collect on Al Shifa. However, even without that requirement, the intelligence community had been monitoring Al Shifa from December 1997 to August 1998, giving them plenty of time to close these collection gaps.

Failures in Analysis

In addition to the collection failures, there were basic analytical failures by the intelligence and policy communities that contributed to the intelligence failure surrounding Al Shifa:

1. Confirmation Bias: Confirmation bias is defined as the tendency of people to see evidence consistent with their preexisting beliefs. It often occurs in analysts who may see certain evidence first, anchor their minds around the evidence, and then incorporate new information around all new data.

In the Al Shifa case, it is likely that the principle analysts or intelligence experts involved (and possibly the intelligence community as whole), anchored their minds around the positive soil sample hit, which was likely interpreted as incontrovertible evidence of the presence of VX. From there, new incoming data was fastened around this belief. If you believe there is already VX, it is likely that you would amplify the supposed links between Bin Laden and the owners of Al Shifa. Subsequently, one can draw the tenuous conclusion that Bin Laden lived in Sudan and, therefore, must have a connection to the Sudanese military's industrial complex. Someone impacted by confirmation bias would downplay the alternative evidence that EMPTA could have commercial applications, or that there were no established connections between Al Qaeda and the owners of Al Shifa, They might also downplay the fact that Sudan had expelled Bin Laden several years earlier, which would dilute the connection between them.

2. Unquestioned belief in scientific evidence: Studies have shown that juries tend to believe scientific evidence with little scrutiny on the merits of the underlying data. It is likely that juries, like the vast majority of the public, have little understanding of scientific data, and are more likely to believe it on face value.

Further, it is likely that analysts and policymakers fell into this trap with Al Shifa. The EMPTA was first reported as conclusive proof for the presence of VX, and nobody questioned the handling of the evidence, potential other uses for EMPTA, how widely prevalent EMPTA was in the environment, or its role as a precursor and not a final product. Like scientific evidence surrounding the Iraq WMD fiasco, scientific evidence rarely gets the scrutiny that other evidence tends to.

3. Negative Evidence: Closely related to confirmation bias, the intelligence and policy communities failed to account for negative evidence regarding the relationship between Al Shifa and chemical weapons production. As mentioned, the intelligence and policy experts were looking for targets and potential links between Al Shifa and Bin Laden. However, the question they should have asked was "if Al Shifa is connected to chemical weapons capability and Osama Bin Laden, what should we be seeing as well?" If these questions had been asked, then analysts would have looked for chemical protective gear, shipping receipts of VX precursor material, importation of high end chemical weapons development, and other indicators that would have been part of a chemical weapons program. In normal intelligence process, negative evidence is used in a "red team" to challenge key assumptions. However, there is no proof that negative evidence was ever visited by the small group.

It is important to note that while these analytical failures are usually attributed to intelligence community analysts, most of these attributes were exhibited by the "small group" policymakers who only had input from Tenet.

<u>Rebuttal Arguments</u>

The primary arguments made for striking the Al Shifa facility were made by Daniel Benjamin and Steven Simon. Benjamin and Simon were National Security Council (NSC) staffers, who were directly involved in the decision-making process around the attack. Their arguments are outlined in their book The Age of Sacred Terror and subsequent article "A Failure in Intelligence."

1. Al Shifa was involved in the production of VX: Benjamin and Simon assert a strong connection between al Shifa and VX gas. They believe that the EMPTA sample provided incontrovertible evidence of an active VX program, and that there was reason for EMPTA to be present.

However, the onsite reporting tells a different story. As mentioned earlier, the plant technical managers and numerous individuals who had visited the plant did not see any evidence of VX production. While they are not chemical weapons experts, it is unlikely that the process of VX production could have been hidden from outside visitors.

Most importantly, if there was a belief that Al Shifa was intimately involved in VX production, why not call for an onsite inspection of the facility after the fact? If the NSC believed that the plant was somehow part of a VX production line, they would want to send out a team of investigators to determine its nefarious connections. The government of Sudan was willing to let outside inspectors in, the only barrier was the US government, which made no determined effort after the fact to confirm VX presence at Al Shifa.[33]

2. VX precursor material was being developed at Al Shifa but not the final product: Benjamin and Simon's argument appears to have evolved to state that VX precursor materials was stored at Al Shifa, and the final product may have been produced elsewhere.[34] While this is certainly possible, much of the precursor material for VX (sulfur, hydrochloric acid) is widely available and has numerous industrial uses. Furthermore, Benjamin and Simon do not say what precursor material it was or what precursor material might have triggered the positive EMPTA hit. From the reading, it appears both men are using the arbitrary "precursor" material, as a way to deflect from the fact that their original rationale---that a full scale VX production facility---was not accurate.

3. The Al Shifa attack was a failure in policy and was not the result of intelligence flaws: In his book Terrorism and Foreign Policy, former CIA counterterrorism analyst Paul Pillar argues that the intelligence was not flawed—that the intelligence was adequate, but the policymakers decided the evidentiary standards necessary to warrant an attack on the facility. According to Pillar:

US Intelligence did not say that al-Shifa should be destroyed; it did not say that an active VX production program was there; and it did not say that destroying the plant would make a difference in bin Laden attacking; or not attacking the United States in the future with chemical weapons….The intelligence did not show what role, if any, al-Shifa may *have ever played in any VX program (production, storage, occasional transshipment, or whatever), nor did it point to any specific plans by Bin Laden to use chemicals in a future attack. The intelligence did not deny that the plant was engaged in legitimate production of pharmaceuticals.*[35]

However, there are issues with Pillar's assertions. While he expresses many caveats, it is apparent that the policymakers received a much different message. As stated above, Chairmen Shelton, Secretary Cohen, and NSC Director Clarke all believed the intelligence showed a stronger connection between VX and the Al Shifa plant. Clearly these caveats were either not introduced or introduced so tenuously that the experts were not aware.

Finally, Pillar argued that the intelligence had been presented; that it was up to the policymakers to decide if evidentiary standard had been met and warranted an attack. In the above sections, however, I argue that Director Tenet should have leaned forward in his analysis, not just presenting the holes in the intelligence, but outlining the drawbacks of the attacks as well as the actual nature of the threat from the Al Shifa plant.

Conclusions and Iraq WMD Comparisons

The Al Shifa incident is a microcosm of the Iraq WMD Intelligence failure. Several of the incidents parallel each other:

- **1. Politicization:** Like the Iraq WMD issue, politicization was an important part of the intelligence debacle. Clinton's requirement for two separate targets, regardless of the security threat, had a cascading effect on the intelligence analysis. In the wake of the embassy bombings, policymakers were now "looking" for a second target, forcing the intelligence community to find connections that were not there. Furthermore, the requirement for a second target forced incomplete intelligence to "bubble up to the top" entering the policymaking community when it was not close to being analyzed or acted on.
- **2. Unquestioned Belief in Scientific Evidence.** Policymakers were enamored with the EMPTA hit, believing that it presented irrefutable evidence of the presence of chemical weapons. As far as information available in the public domain, none of the senior principles asked if EMPTA may have had legitimate commercial uses or whether there were errors in the handling and collection of the soil sample. Like the Iraq WMD assessments on the aluminum tubes or the purported evidence of mobile labs, it seems scientific evidence is rarely scrutinized after it enters the policymaking community.
- **3. Inability to Analyze Negative Evidence.** Policymakers in the Al Shifa attack were on the lookout for evidence tying Al Shifa to chemical weapons facilities. However, they were not asking the reverse question--i.e., if there was an active VX program centered in the Al Shifa plant, what else should we be finding? If that question had been asked, then the intelligence community would have looked for importing of precursor material, presence of protective gear, other indicators that chemical weapons were being produced or stored at Al Shifa. These same issues were visible in the Iraq WMD case where analysts found evidence of Iraq WMD presence, but did not ask the larger question of "why are we not seeing more indicators if Iraq is pursuing an active WMD program."
- **4. Backdrop of a National Trauma:** The Al Shifa evidence was analyzed under the backdrop of the embassy bombings in Tanzania and Kenya. This provided an artificial time constraint and an impetus to find evidence that might not be there. Again, this parallels the Iraq WMD case where the 9/11 attacks certainly pervaded the analysis of policymakers and the intelligence community.

The consequences of the attack were enormous. Not only was a civilian killed and ten others wounded, the destruction of the Al Shifa plant robbed Sudan of a vital supply of pharmaceuticals that the already impoverished nation desperately needed. More importantly, it advanced the Al Qaeda narrative of being "picked on" by a larger, more powerful country. This issue would ultimately be exploited by Al Qaeda, especially in the run up to 9/11.

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