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Mailing Address:
Director, USANCA, 5915 16th Street Building 238, Fort Belvoir, VA 22060-1298.

Telephone: 703-545-9812, Fax 703-806-7900, DSN 94-312-545-9812..

Electronic Mail: usarmy.belvoir.hqd-dcs-g-3-5-7.mbx.usanca-proponency-division@mail.mil
Subject line: ATTN: Editor, CWMD Journal (enter subject)

About the cover: 2ID Soldiers moving through a simuated CWMD contaminated environment. Picture from Joint Program Executive Office for Chemical, Biological, Radiological and Nuclear Defense-JPEO-CBRND

Inside the Journal

Director Notes

COL Benjamin Miller
Director, USANCA

Since our last publication of Countering WMD Journal, USANCA has made significant progress on a number of important efforts to improve the ability of the Army, the CWMD Community, and ultimately, the Joint Force to deter adversaries and, when necessary, fight and win our Nation's wars. I am proud of the progress we have made.

Conventional Nuclear Integration (CNI)

As the Force Management Proponent for all things nuclear, USANCA is leading Army efforts to reform five areas, focused on the human dimension, of Army's readiness to conduct operations in and through a nuclear environment. These areas are doctrine, education, training, planning, and exercises. Implementing these reforms are part of the larger complex problem of modernizing and readying the Army to fight and win on the nuclear battlefield. By leveraging what the Army does every day – train for war – we will apply the Army's core competencies to prepare leaders and units to operate under the threat or employment of nuclear weapons.

Anticipated later this summer is the tactical-leader focused ATP 3-72 Multi-Service TTPs for Operations in a Nuclear Environment publication. In partnership with our sister services, USANCA will continue to lead and support additional doctrine development. This spring, USANCA will initiate with TRADOC a cross-Army working group to produce a CNI training strategy as input to the Army Training and Leadership Development Strategy. The working group will produce education enabling and learning objectives, as well as update existing training to reflect the current nuclear threat. The product will also inform the ReARMM process, which is critical to ensuring the Army meets its responsibility to provide trained and ready forces for joint operations. Later this summer, the Army is placing USANCA Nuclear and CWMD Planners (FA-52s) at USCENTCOM, USARPAC and USAREUR-AF. This will not only add capacity to these commands' nuclear planning teams, but also enable rapid integration of Army equities with theater needs. Finally, USANCA and other Army stakeholders are working to evaluate CNI tasks in Army and joint exercises. The goal is to include CNI training objectives for operational and tactical units through Warfighter TTXs and CTC/JRMC exercises, as well as for strategic planning through TAA and other concept validation exercises. This will enable the Army to demonstrate its nuclear warfighting proficiency to our Allies and Partners, and to refine our training objectives in multi-national exercises.

Biological Defense

Traditionally, Army biological defense has focused on biological warfare and has been the responsibility of the CBRN defense and medical communities, with minimal demand signal generated by operational commanders. As the COVID-19 pandemic demonstrated, biological risks to the Army's mission do not come solely from man-made threats, but can also include naturally occurring outbreaks of disease.

Because of the complexity associated with responding to both man-made and naturally occurring threats, USANCA, in conjunction with other partner organizations, developed the Army Biological Defense Strategy (ABDS) 2021, which was signed into publication in March. The purpose of the ABDS is to maintain the Army's capability and capacity to accomplish its mission and to ensure readiness in the face of biological threats and hazards to support the Department of Defense (DOD) and the Nation. The ABDS creates structures, processes and policies to drive Army investment, planning, and preparation to enable Multi-Domain Operations in the face of biological threats and hazards.

Going forward, a Transition Team with broad participation from members throughout Headquarters Department of the Army will work to begin implementation of the strategy in order to meet objectives contained within the Army Campaign Plan. Additionally, the Army will work with the Office of the Deputy Assistant Secretary of Defense for Chemical and Biological Defense to facilitate their efforts and ensure synchronization as they develop a biological defense strategy that will apply DoD-wide.

Survivability

Chief of Staff Paper #1 (Army Multi-Domain Transformation, 16 March 2021) describes the asymmetric advantages of land forces with the ability to maneuver and communicate rapidly, strike at range, and survive in complex terrain. A landpower force with such abilities enables greater decision dominance and overmatch. Army forces capable of surviving adversary counterstrikes create overmatch by their ability to attack throughout the depth of the battlespace. The Army increases readiness against near-peer adversaries possessing CBRN threats when tactical and operational formations are capable of fighting, surviving, and winning on the future battlefield.

Operational survivability (materiel and personnel) on the battlefield is a large effort. The Army acknowledges this broad effort will require working within DoD (e.g. Defense Threat Reduction Agency and Defense Intelligence Agency) and interagency partners. Importantly, the Army recognizes that capabilities, characteristics, and abilities once inherent within our structure during the Cold War have atrophied and will need to be reenergized. USANCA is taking action to address operational survivability within doctrine and subsequent implementation in a nuclear and CBR environment. USANCA's actions will contribute to the understanding of operational survivability as a characteristic of the fielded materiel and soldier capabilities. In this manner, commanders at echelon can better assess available combat power following an engagement where weapons of mass destruction are used. The landpower component is a critical part of our Nation's deterrence and increases the national and collective allied strength to a level where adversaries will either compete with less ambitious aims or forego competition altogether (Chief of Staff Paper #2, The Army in Military Competition, 1 March 2021).

Diversity and Inclusivity

Although the above initiatives are vital to our preparedness, these reforms alone will not win our Nation's wars--our people are our greatest source of strength! A diverse, inclusive Army is our most lethal weapon system. To this end, we have also recently developed a strategy to fully embrace a diversity of backgrounds, experience, and thought across the Functional Area 52 (FA52) community, for whom USANCA serves as the proponent. This initiative draws on the strengths of a diverse Officer Corps in an inclusive environment by investing in and managing talent, valuing individuals, and developing officers who enhance their organizations and are prepared for the human dimension of leadership. We will establish a Diversity Committee to assess the current environment in terms of diversity and inclusion, identify actions to propagate diversity and inclusion across the FA52 force, and advise FA52 senior leaders. One of the near-term goals is to focus FA52 recruiting actions to increase the number of female and minority officers in the FA52 work force. The benefits of the FA52 diversity efforts are many, including the opportunity to better understand our Army's increasingly diverse population and attract the best available talent to join the FA52 ranks. The many different attributes and experiences of a diverse FA52 workforce will enhance our ability to operate globally in support of Army, joint, and interagency organizations.

I hope you enjoy our 22nd issue of Countering WMD Journal! I encourage each of our readers to spread the word that USANCA is always searching for future contributions to our publication. Also, please keep an eye on USANCA's progress and stay connected to the Countering WMD Community by following us on LinkedIn, at https://www.linkedin.com/company/usanca/.

The Negatively Pressurized CONEX Lite system is placed inside an Air Force C-130 Hercules. The system is designed for transporting COVID-19 diagnosed and symptomatic warfighters out of forward installations and on to medical facilities. Picture by DEVCOM CBC

The inside of the NPC-Lite includes ambulatory patient seating (left) and litters with medical equipment (right)

COVID-19: A Case for Bioterrorism Awareness

CPT Matthew E. Bertram
1st Armored Brigade Combat Team, 1st Cavalry Division

The Corona Virus Disease (COVID-19) pandemic demonstrates the devastation a biological agent can have on a globalized, modern society. The recent outbreak of COVID-19 highlights the impact bioweapons have on strategic assets and accentuates the shortcomings of the U.S. biodefense strategy and DOD (U.S. Department of Defense) response. This paper will describe COVID-19 impacts economically and to the U.S. military, examine gaps in the U.S. Biodefense plan, and outline the similarities of COVID-19 to emerging second generation synthetic biological threats. The conclusion offers three areas upon which to focus future policies; leadership, biosurveillance, and homeland preparedness

Introduction:

Late in 2019, a novel virus outbreak was discovered in Wuhan, China. Closely resembling Severe Acute Respiratory Syndrome - Associated Corona Virus (SARS-CoV), this new virus was titled SARS-CoV-2, with an associated disease termed COVID-19.[1] Since the first known national case in Washington in January,[2] COVID-19 has resulted in more than eight million confirmed cases and over 200,000 deaths in the United States as of October 2020[3]. In addition to causing medical casualties the COVID-19 pandemic has caused an economic downturn, decreased military readiness and deployability, and has been detrimental to many manufacturing industries directly related to national defense. COVID-19 has shown the world the limited preparedness of the United States and others to deal with a bio-agent outbreak on a national level.

COVID-19 is a disease primarily spread via respiratory droplets between persons in close contact and has a global mortality rate (death per confirmed infection) of approximately 2.7%.[4] Although a low mortality rate compared to some other viruses, such as Ebola (approx. 50%)[5], the infection rate of COVID-19 is high due to the mechanism of transmission. This is what drives the extensive positive case numbers above. The COVID-19 pandemic was caused by a naturally occurring virus. This outbreak has proven the catastrophic effects and lasting devastation that would transpire if a man-made, engineered patho-

CPT Matthew E. Bertram is the Brigade Chemical, Biological, Radiological, and Nuclear Officer in Charge (CBRN OIC) at the 1st Armored Brigade Combat Team, 1st Cavalry Division, in Fort Hood, Texas. He has a B.S. in Biology with a focus in Microbiology and Immunology from Virginia Tech, and a M.S. in Defense and Strategic Studies with a focus in Countering Weapons of Mass Destruction from Missouri State University. He was previously assigned as a Battalion CBRN OIC at 2-3IN BN, a Platoon Leader of a Hazard Assessment Platoon, and then Company Executive Officer while at 110th CBRN BN based out of Joint Base Lewis-McCord. His email address is matthew.e.bertram.mil@mail.mil.

gen was released. Modern day science has, theoretically, made it possible to generate a bioweapon that pairs the transmission rate of COVID-19 with the mortality rate of Ebola. Instead of 200,000 deaths in the U.S., the nation would be facing more than four million dead, hospital and mortuary services would be overwhelmed, and a greater degradation to national security would occur.

For the purposes of this paper, the assumption is made that all nations and non-state actors have the "will to use" bioagents. The focus will be on identifying impacts to national security, current and emerging biothreats, current biodefense vulnerabilities COVID-19 has exposed, and how lessons learned from COVID-19 can be used to improve policies to better prepare against and deter biowarfare and bioterrorism threats in the future.

All sources used for the construction of this paper are unclassified and available on open source media. COVID-19 is an ongoing pandemic and numbers are changing daily. All metrics, projections, and data used in this paper are current and accurate as of October 2020.

COVID-19 Impacts:

In addition to the well documented casualties, COVID-19 has directly impacted multiple aspects of U.S. national security: an economic downturn, decreased military readiness, stress on national medical assets, and an inability to ascertain who may be infected. All the above could be strategic goals of an adversary's biowarfare program.

Economic Impact

Although still functioning, and recovering, the U.S. stock market and employment rates were adversely affected by COVID-19. The DOW alone plummeted by 37% between February 12 and March 23 of 202048 . While the stock market is not a holistic view of the U.S. economy it does tend to provide a realistic representation of general economic trends. The National Bureau of Economic Research (NBER) conducted a study in April 2020 to ascertain the impact COVID-19 had on the U.S. stock market. The NBER found "no previous infectious disease outbreak, including the Spanish Flu, has impacted the stock market as forcefully as the COVID-19 pandemic."[6] The NBER study focused on market fluctuations as an indicator of instability and lack of confidence in the U.S. economy.

Economists have identified multiple factors for the fluctuations of the stock market during this pandemic directly related to COVID-19. The most prominent factor is that COVID-19 is highly transmissible in a public setting. Unlike other recent out breaks such as Zika or Ebola, which function via different mechanisms of transmission, COVID-19 can be passed via a simple in-person conversation. The U.S. economy has also shifted over time towards consumer and business services, which often involve face-to-face interactions in close physical proximity.[7] This has led to voluntary isolation and a decreased participation in the service economy.

Another reason for market volatility has been the implementation of nonpharmaceutical policy interventions (NPIs). These policies include limiting or preventing international travel and mandatory closure of non-essential businesses. As implementation of these policies took effect in March and April 2020 there was a noticeable increase in market fluctuations.[8]

Unemployment has also spiked during the outbreak, topping an estimated 60 million claims for unemployment since January 2020.[9] Prior to the COVID-19 pandemic the highest number of insurance claims in one week was 695 thousand claims in 1982. Starting in March 2020, there were 20 consecutive weeks of over one million insurance claims a week.[10]

Between unemployment, market fluctuations, and loss of life, the total cost of the COVID-19 pandemic from January 2020 through October 2020 is estimated at more than $16 trillion, approximately 90% of the annual gross domestic product of the United States.[11] This is a number derived from less than one year under COVID-19 conditions, with no FDA approved vaccine in production. The loss of nearly 90% of GDP is a grave national security risk, limiting ability to trade in a global market, produce and modernize the military fleet, and maintain U.S. presence and support overseas.

Military Readiness

Identifying the true readiness of the U.S. military requires delving into confidential statistics or sensitive data. Assumptions can be made based on public releases and deviations from previous operating procedures and routines. The inferences in this paper are based solely on what is publicly available and may not represent the "ground truth" identified in other classified mediums.

There have been four major impacts to military readiness with the rise of COVID-19: (1) the direct casualties and deaths, (2) the reduction and prohibition of travel, (3) the delay and elimination of large collective training exercises, and (4) the diversion of resources and personnel to COVID-19 response.

There have been over 38,500 confirmed COVID-19 cases among service members across all branches of the military since the beginning of 2020, including seven deaths.[12] Although a fraction of the total military (roughly 2% positivity rate)[13] are contracting COVID-19, it is important to recognize the strain this puts on the individual units when personnel become non-deployable. Many military units are not structured to have redundant positions (i.e. one pilot per plane, one driver per tank) this means the loss of one service member can equate to the loss of a whole weapon system. Subsequently, what appears to be only a 2% degradation of manning rapidly increases to upwards of 10% of systems being non-mission capable without the appropriate personnel.

The Department of Defense (DoD) issued a stop move early during the pandemic; this restriction stretched through the summer transition months.[14] The stop move was an attempt to stop COVID-19 from spreading, as individuals would need to conduct travel across state and international boundaries. This stop move affected both deploying units as well as individual service members. The policy resulted in a direct degradation of national security as units could not deploy forward and units already forward deployed could not receive inbound soldiers for a period over six months.

In order to prevent large "spreader" events of COVID-19, the DoD has limited and reorganized training at the "collective" level. Collective training refers to any training above a platoon sized element, approximately 30 individuals. Under COVID-19 conditions the Army has canceled more than three National Training Center (NTC) rotations, as well as multiple other Combined Arms Training Center (CTC) rotations.[15] The NTC frequently hosts the culminating training exercise as units prepare to deploy; it is the closest simulation of actual combat operations the United States military can achieve. With the inability to train at these events, elements across all branches of the military cannot integrate and train together. The lack of training vastly degrades combat readiness. Consequently lessons that could be learned at NTC would now have to be learned in war if a conflict were to arise.

Beyond the impact of intentional cancellation of training, the military has also been called upon to support the national COVID-19 response. This support has been both resource and personnel intensive, drawing on active, reserve, and national guard service members and supplies. The Army and Air National Guard have sent more than 44,500 troops across the nation to assist efforts to respond, mitigate and control the COVID-19 pandemic.[16] The United States Navy has deployed two hospital ships and associated crews to provide medical support in both New York and California.[17] In addition to these efforts, service members have been tasked with sanitization of installation facilities, conducting contact tracing, and treatment of both military and civilian personnel on DoD installations.

While all COVID-19 support is necessary and assists the nation in controlling the pandemic, it still degrades military readiness. Supporting these additional mission sets takes training time, personnel, and materials away from the military branches' primary mission and decreases overall military capability and readiness.

National Medical Stock

The United States funds and maintains a strategic national stockpile of medical supplies, vaccines, and equipment. Through the course of this year that stockpile was emptied or severely depleted in many areas. "In the early stages of the COVID-19 response, many states, local public health departments, and hospitals were simply unable to purchase personal protective equipment and testing supplies."[18]

This manufacturer shortcoming led to mass requests of federal aid through the national stockpile. The medical supply needs for the initial phases of the COVID-19 response far exceeded the federal reserve of medical supplies in the Strategic National Stockpile.[19] This depletion of the stockpile presents multiple risks to national security and degrades the United States ability to respond to natural disasters, subsequent disease outbreaks, or other military requirements in an efficient manner.

Disease Tracing

COVID-19 has exposed deficits in the biosurveillance programs operating within in the United States. Two main deficiencies were identified; the inability to rapidly contact identified cases and the failure to accurately aggregate data to represent the true reality of COVID-19 spread. The delays and incomplete reporting of COVID-19 cases led many news outlets and policy makers to use alternative sources outside the CDC (Centers for Disease Control and Prevention), i.e. John Hopkins University.[20] Outdated technology at all echelons of local, state, and federal organizations were shown to prohibit a rapid surveillance program capable of tracking positive cases and contacting trace personnel once identified.[21] This shortcoming has allowed the virus to continue to spread, increasing the overall susceptibility of the nation to a pandemic and magnifying all the threats to national security listed above.

Bioagent Threats:

Technology in the biological sector is ever changing. Advances have sprung innovations that rid the world of some ailments (i.e. smallpox) while vastly reducing the mortality of others, such as AIDS and various forms of cancer. These growing advances have also allowed nations and non-state actors to harness some of the world's deadliest diseases and toxins for use in biological warfare. Bioagents such as weaponized anthrax, botulinum toxin, and ricin have all been utilized. Technology is now advancing to a point where those who wish to cause harm can modify already existing pathogens to overcome natural immunity or even drug therapies.[22] There exist two main biological agent concerns; the weaponization of a natural pathogen and the growing threat of synthetic biology.

1st Generation

Weaponization of natural pathogens has a well-documented history. Early examples of weaponized biological agents include the distribution of smallpox blankets to Native Americans by the British and the testing of multiple biological agents on the Chinese population by the Japanese Imperial Army in World War Two (WWII). Post WWII bioagents have been more frequently targeted at the civilian population, as opposed to a strategic target on the battlefield. Modern attacks include the Salmonella poisoning in Oregon attributed to the Rajneeshee cult in 1984[23] and the more recent 2001 "Amerithrax" attack, disseminating weaponized anthrax through multiple United States Postal Service locations en-route to elected officials.[24]

As described in the book Biohazard, the Soviets under director Ken Alibek produced these 1st generation bioagents in mass. The Soviets weaponized anthrax, smallpox, and botulinum toxin, among others.[25] Through the course of Alibeks' time, thousands of pounds of bioagents were produced, some of which still remain unaccounted for following the fall of the USSR.[26] These bioagents remain a threat facing the United States, whether it be the Russian military wielding them or a non-state actor looking to deploy it in a U.S. territory.

2nd Generation

Unlike first generation biothreats which are weaponized naturally occurring pathogens, second generation biothreats are created using synthetic biology. Second generation threats loom as a very real possibility, even if none have been employed against the U.S. to date. Synthetic biology lowers the barriers for development of bioagents, putting them within reach of less resourced actors.[27] Unlike first-generation bioagents where the concern lies within organizations acquiring stock material to seed their weapons, second-generation threats revolve around the ability to acquire and use the advancing biotechnology currently available. From this technology the National Academies of Science, Engineering, and Mathematics (National Academies) identified three major categories of bio-threats: pathogen related threats, the production of biochemicals, and bioagents capable of altering the human host.[28] For the purposes of this paper the focus will be on those threats related to pathogens, similar to COVID-19. Pathogen related threats can further be broken down into four subsets: re-creating known viruses, recreating known pathogenic bacteria, modifying existing pathogens, and creating new pathogens.

In an effort to advance healthcare and improve vaccine programs, many known virus DNA sequences have been made publicly available on digital databases. In decades past, it was difficult to "assemble" DNA from scratch in a specific sequence. With advances in biotechnology it is now possible to assemble larger and larger viral genomes. For example, horsepox, a viral genome larger than 200 thousand base pairs, was constructed in 2009 and suggests that virtually any virus, with a known sequence, can be constructed with no "stock virus" needed.[29] For reference, Ebola virus is 19 thousand base pairs and SARS-CoV-2 is slightly larger at 30 thousand base pairs.[30]

Although not currently available, similar technology is in development to produce known pathogenic bacteria. Bacterial genomes are larger and can fragment when handled during normal laboratory procedures. In addition to fragmentation, bacterial genomes need to be "seeded" into an existing cellular structure which further complicates the design process.[31] As advances continue it is important to monitor and re-evaluate the feasibility of re-creating pathogenic bacteria as it will remain a national security risk.

With current technology it is possible to enhance pathogenic properties of both bacteria and viruses given time, testing ability, and correctly trained subject matter experts. In many ways, modifying a known virus is more complicated than simply recreating the virus itself. The largest roadblock in this process is the modification of the viral genome. This modification can often knockdown or remove other vital components of the genome specific to that virus' success.[32] Bacterial modification is a better understood and more reliable process. It has been shown across a multitude of procedures that scientists have been able to alter bacterial genomes to enhance things such as drug resistance and toxin production.[33] Both viral and bacterial modifications present a significant bioagent threat as our understanding of genomes and DNA manipulation continue to advance.

The last subset of second-generation bioagent threats is the creation of new or novel pathogens. Although the least likely to occur of all the threats discussed, in many ways a novel pathogen would be the most dangerous outcome. A novel, engineered pathogen would be considerably dangerous due to the difficulty of initially identifying it, the lack of effective prophylaxis or medical countermeasures available, and the extended testing and production time required for any new vaccine. The creation of a new pathogen would require in-depth scientific knowledge, training, and an extended period for testing. The technology is currently present to produce such pathogens; it is the knowledge of genome viability and stability that is lacking. To date, the closest replication of a new virus has been the creation of a nucleocapsid (a protein capable of packaging its own genetic material) in 2017.[34] Again, close monitoring of this technology is necessary to re-evaluate threat levels as design processes continue to develop.

Current Mitigation:

Current biowarfare policies and prevention measures in the United States are based largely on and expand upon the 1972 United Nations Biological Weapons Convention (BWC). There have been eight review conferences of the BWC, with the most recent occurring in 2016.[35] The original BWC focused on the disarmament and reduction of biological weapons stockpiles. The BWC has since expanded to state:

"Under these agreements, the States Parties undertook to provided annual reports – using agreed forms – on specific activities related to the BWC including: data on research centres and laboratories; information on vaccine production facilities; information on national biological defence research and development programmes; declaration of past activities in offensive and/or defensive biological research and development programmes; information on outbreaks of infectious diseases and similar occurrences caused by toxins; publication of results and promotion of use of knowledge and contacts; information on legislation, regulations and other measures."[36]

This convention lays the foundation of how the U.S. maintains awareness of possible bioagent production among those countries cosigned on the BWC. The drawback is many countries, including Iraq and Russia, have continued to produce and enhance biological agents in direct violation of the BWC. Violations of this treaty are well documented over time, including in both publications: ***Germs***[37] and ***Biohazard***.[38] Production and enhancement methods rely mostly on self-reporting. While inspections are aimed at identifying known pathogen stockpiles, there is little that addresses the threats created by advancing biotechnology.

Since the 2001 "Amerithrax" attack, the U.S. has allocated additional funding and created policies which address the growing threat of bioterrorism.[39] In 2001, emphasis was placed on biosurveillance, including the President's Bio-Surveillance Program Initiative. The purpose of which is to identify outbreaks as soon as possible to limit the spread while simultaneously collecting data to assist in treatment and prevention. The second notable outcome of the Amerithrax attack was the Bio-shield Act, again allocating additional funding for bio-defense and driving the creation of additional vaccine stockpiling while allowing for the use of a non-FDA approved vaccine if deemed critical to national security.[40]

The most recent National Biodefense Strategy (2018) places emphasis on the following five goals: enable risk awareness to inform decision making across the biodefense enterprise, ensure biodefense enterprise capabilities to prevent bioincidents, ensure biodefense enterprise preparedness to reduce the impacts of bioincidents, rapidly respond to limit the impacts of bioincidents, and facilitate the recovery to restore the community, the economy, and the environment after a bioincident.[41] Although the above goals focus on preventing the acquisition and spread of known bioagents, there is little to no architecture for monitoring advancing technologies and capabilities.

Shortcomings of U.S. Biodefense

If COVID-19 has shown anything, it is that the United States was not prepared for a novel pathogen on the scale of a global pandemic . There are national disease response related policies and practices to be corrected. Many of these corrections can be expanded to prepare against biowarfare and bioterrorism, not just naturally occurring diseases.

Shortcomings of the United States Biodefense Strategy were identified prior to COVID-19 during an examination by the Government Accountability Office (GAO) in February 2020. These flaws included a lack of planning and guidance to support a whole federal government approach, a need for guidance and methods to meaningfully analyze the data regarding existing federal biodefense programs and activities, and a need to clarify the decision-making processes, roles, and responsibilities. In essence, GAO identified the 2018 biodefense strategy as noble aspirations with little guidance on how to accomplish the task.

The Crimson Contagion Functional Exercise Series was a two-year examination of our healthcare response to an epidemic, culminating in August 2019. This exercise highlighted many shortcomings that were also evident during the real world response to COVID-19. First, it was identified that the U.S. manufacturing industry and supplies would not support global demands during a pandemic. Second, the department of Health and Human Services (HHS), the organization named in the biodefense act as lead, does not have the finances, resources, nor the authority to effectively respond without subsequent authorizations from Congress. Lastly, policies do not currently spell out directed roles and responsibilities across organizations such as FEMA (Federal Emergency Management Agency) and the CDC. This has led to duplicate efforts and conflicting information between government organizations.

Funding and research have also suffered over the last decade. Looking at the federal budget since 2004, both the public health emergency fund and hospital preparedness program have steadily received cuts. In 2004, the two funds combined for just over

1,400 million USD annually; by 2020 that number had been cut to 900 million USD annually. The lack of funding has directly affected medical supplies available as part of the national stock, mirroring the decline in federally funded research into pathogens. The United States needs to continue innovative research in biotechnology if future bioagent threats are to be mitigated.

Two additional shortcomings of U.S. biodefense prepardness were identified in PCAST's (President's Council of Advisors on Science and Technology) 2016 letter to the President. The first being that the 2016 " watchlist" and vaccine development list is organized around approximately 60 pathogens. Advancing biotechnology and the ability to construct both novel viruses as well as re-create pathogens without seed stock creates challenges with having an effective watch list. If no seed stock is needed, it eliminates the ability for intelligence organizations to flag individuals in the act of acquiring the known substance, because they can now make their own with no paper trail.

A second shortcoming identified that biosurveillance should cover both national and international areas of concern and trace spread. With COVID-19, the U.S. was not able to identify the threat prior to arrival within the states. Once the pathogen started spreading, the U.S. biosurveillance program was unable to trace and quickly identify cases or pertinent data. This program will need to be boosted both nationally and globally in order to effectively and rapidly identify and trace natural or synthetic bioagents. While not able to pick up a truly clandestine bioagent program, if improved, the biosurveillance program may identify possible testing of bioagents, and/or prevent the disease from spreading outside a local area by early identification and accurate tracing of contacts.

Why Use COVID-19 as a Comparison?

Besides the obvious fact that both events involve a pathogen, COVID-19 shares many properties of likely emerging bioagents. Firstly- it is a novel disease, previously unknown to the scientific community. The base architecture of Corona virus was previously identified in SARS, but this particular variant had not been studied. This is likely to occur with emerging biothreats. Similarly, the United States may have to respond to an unknown outbreak and quickly assess symptoms and shared indicators without fully understanding the pathogen it faces.

Secondly- the disease traveled from outside our borders. Unlike some conventional weapons that would need to be brought in and assembled or deployed here in the United States, pathogens can be fully developed and released outside our borders with no chance for interdiction within U.S. jurisdiction.

Thirdly- there was no previously existing vaccine, prophylaxis, or identified effective antiviral treatment for SARS-CoV-2. This is a desirable trait for those wishing to cause harm with modern biotechnology. If possible, bioagents would be designed to resist therapeutics and evade natural immunities. Both traits would allow for greater virulence and increased casualties.

Lastly- COVID-19 has a relatively high infection rate compared to other diseases. When designing bioagents, there will be an emphasis on creating a pathogen with virulence high enough to cause an outbreak. It does no good from a bioterrorism stand point to release an agent that struggles to effectively infect individuals.

For all the above reasons the assumption can be made that if a modern engineered bioagent was utilized against the United States it would - at a minimum - be as detrimental to strategic assets as the COVID-19 pandemic.

Conclusion:

It is imperative the United States looks to lessons learned during the COVID-19 pandemic and adjust the National Biodefense Strategy accordingly. The degradation to military readiness addressed above is a direct result of the inability to properly manage or prevent an outbreak. With a more robust biodefense plan these impacts and degradation to national security may be lessened or avoided all together. As more technology becomes available, pathogens become more customizable allowing for the creation of a bioagent that does not target the organization releasing it. Due to this advancing technology, the release of a bioagent can be a strategic tool to be utilized against whole nations. As such, there are three recommended policy focus areas which should be addressed: leadership, biosurveillance, and homeland preparedness.

First, as noted across multiple exercises, evaluations, and during the COVID-19 response, there has been inconsistent U.S. national response leadership and ever changing roles and responsibilities with regards to biodefense and disease response. Moving forward there needs to be a permanent, consolidated, biodefense arm of the Department of Homeland Security, not just a steering committee as currently formatted. An office could either stand up under the current Countering Weapons of Mass Destruction office or act under a new assistant secretary position. In either structure, its purpose would need to expand to include pandemic response and monitoring. This subset of the DHS would be a more flexible entity with greater scope than the small C-WMD section as it is drafted currently. Importantly, it would be granted interagency control not reliant on repeated requests for congressional authority at every step. The organization would be capable of planning and coordinating across multiple agencies including the CDC, FEMA, DHS, HHS, NBACC (National Biodefense Analysis and Countermeasures Center), NIH (National Institutes of Health), and DoD. This DHS program would be manned by assistant secretaries of the aforementioned organizations who have been empowered to reallocate and grant access to resources required for full biodefense preparedness and response.

This office would be responsible for monitoring possible outbreaks, directing intelligence collection of bioagents, administering allocated biodefense funds, and heading the nation's response to naturally occurring or man-made pathogens. In addition to the above, this entity would recommend biodefense research requirements and medical stock updates based on the feedback of biosurveillance and intelligence collection.

Second, the United States needs to expand and improve the biosurveillance program. The program needs an increased focus on monitoring international disease outbreaks and bioagent technology acquisition, while health data collection efforts at home need to be synchronized. Additional funding needs to be provided to standardize and modernize state and local level collection assets, ensuring the capability of feeding a larger national network. This updated program will eliminate conflicting reports and aggregate data in a way it can be rapidly assessed and acted upon. The advances in both computer sciences and biotechnology should enhance the ability to flag patterns and feed medical countermeasures. In addition to national biosurveillance, the U.S. needs to expand this program for global inputs. With current globalization and ease of travel, an outbreak remote in Africa may soon travel via aircraft to the heart of the United States. This was made evident with the Ebola outbreak. The only way the U.S. can truly prepare and prevent spread of an outbreak is identification prior to landfall.

The biosurveillance program would also act as a countermeasure against manufactured bioagents. If sensitive enough, the program would be able to ascertain possible test populations and any novel pathogens introduced to the environment.

The focus of data collection needs to shift away from solely identifying known pathogens and move towards platform and knowledge bases. Identifying key indicators and personnel will soon be more critical than identifying individual organisms or controlled substances.

Third, the need for homeland preparedness improvements are twofold. One, they reduce the casualties and strategic detriments identified in the first part of this paper, leading to an increase in military readiness while decreasing the disease support requirements of military units within the United States. Two, it acts as a form of deterrence to bioterrorism. If it is known that policies, procedures, and safety protocols are in place to prevent a widespread epidemic, adversaries may deem it no longer cost effective to utilize bioagents against the United States.

There are three major preparedness improvements needed. The first is to push additional medical stockpiles to state juridictions, while maintaining the national stockpile. It was identified during COVID-19 that current stockpiles are insufficient and delays in transportation lead to lives lost. An increase to overall stockpiles of PPE and medical countermeasures, held at both the state and national level, will alleviate this shortcoming. Second, additional resourcing of medical countermeasure research is needed. This research should be focused on platform technology rather than individual vaccine research for specific pathogens. The development of a "plug and play" platform which can generate vaccines or other medical countermeasures based on input from any pathogen is critical when the next bioterrorism attack may incorporate a bioagent never before seen. Lastly, continue to increase funding into synthetic biotechnology research. If the U.S. can develop further approximations of what the next threat may look like, the biodefense enterprise is one step closer to combating it and emplacing effective deterrence measures.

We now have an obligation to learn from this experience and take decisive steps to better prepare for the future… Because — like all previous pandemics — COVID-19 too will shift from center stage. The public will have had their fill. The danger will seem removed."[42]

Former Majority leader, Senator William Frist, M.D.

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How Does COVID-19 Impact State Biological Warfare Program Strategy?

Theodore R. Plasse and Ranée K. Rotter
Defense Threat Reduction Agency RDCXQ / USSOCOM CWMD Support Program

The COVID-19 pandemic provides real-time insight into state and societal vulnerabilities and preparedness for a contagious disease outbreak. The effects of the COVID-19 pandemic have not yet been fully realized; as the waves of infections begin to decline, the socioeconomic impacts are swelling. Several projections indicate that the pandemic will cause political instability in some countries with the potential for further disruption across the world. It is a reasonable assumption that state responses are being analyzed by adversaries to assess ways to exploit exposed vulnerabilities and strengths. It is also plausible that a state, with or without a Biological Warfare (BW) program, is examining the pandemic and assessing the effects in context of developing and deploying biological weapons.

How might the COVID-19 pandemic affect a state's interest in BW? Traditional state BW programs, which generally began around the Second World War, focused on degrading the enemies' ability to engage on the battlefield. With that objective, most countries developed weapons capable of disseminating biological agents over a large area populated with a concentration of troops to cause a lethal or incapacitating effect (Office of Technology Assessment United States Congress 1993). Because of the risk posed to the deploying country, programs from this era rarely had interest in agents with significant human-to-human transmissibility. As the Cold War came to an end, the nature of warfare changed. The Biological and Toxin Weapons Convention (BTWC) has effectively solidified the moral reproach against bioweapons though several states are suspected of retaining offensive BW programs. As a result of the COVID-19 pandemic, it is possible that other countries may have a renewed interest in developing offensive BW programs.

Mr. Theodore R. Plasse is the Analysis and Planning Team Chief for USSOCOM CWMD Support Program (SCSP) and a recognized Biological Warfare expert. He has a B.S. in Biology from Siena College of New York, a M.S. in Ecology from Central Washington University, Washington. Mr. Plasse is a retired US Army Military Intelligence Officer and has over 25 years' experience in the IC working WMD issues. His email address is Theodore.r.plasse.civ@mail.mil

Ms. Ranée K. Rotter is the Sr. Biological Threats Subject Matter Expert for DTRA-RDCXQ/ SOCOM CWMD Support Program (SCSP) in Virginia. She has a B.A. in Education from The College of Notre Dame of Maryland, a M.S. in Biotechnology from the University of Maryland, and a M.S. in Applied Intelligence from Mercyhurst University. Ms. Rotter is a contractor with Booz Allen Hamilton and has 18 years of experience in CWMD. Her email address is ranee.k.rotter.ctr@mail.mil.

Statistics on Fatal Coronavirus Outbreaks

- **SARS** – Sudden Acute Respiratory Syndrome
  - 2002-2003 outbreak timeline
  - >8,000 infected
  - 26 countries experienced cases
  - ~11% of infected died
  - SARS spread to ~3 people/individuals infected
- **MERS** – Middle East Respiratory Syndrome (NOV 2019)
  - 2012 to present
  - 2,494 infected
  - 27 countries experienced cases
  - 34.4% of infected die
  - MERS spread to <1 person
- **COVID-19** (17 APR 2020)
  - 2019 to present
  - 2,214,861 infected
  - 185 countries with cases
  - 6.8% of infected die (150,948 deaths reported)
  - COVID-19 spreads to ~6 people/individuals infected (Steven Sanche 2020)

Figure 1. Statistics on Fatal Coronavirus Outbreaks

SARS-CoV-2 Virus

SARS-CoV-2 is the causative agent of COVID-19; the virus is a member of the coronavirus family. Seven strains of coronaviruses are known to infect humans: six cause common colds, and the other three cause serious respiratory diseases, including COVID-19. Coronaviruses look like spheres covered with spikes; the spikes are proteins that bind into human epithelial cell receptors to replicate. Once the SARS-CoV-2 virus begins replicating, it increases virulence by producing a substance like liquid soap further spreading the infection deep into the lungs. In the worst cases, the immune system goes into hyperdrive to rid the lungs of the disease but causes significant damage to the lungs in the process. Lung lesions from COVID-19 infections range in size from a grape to a grapefruit (Neuman 2020).

What Adversaries Have Learned from the COVID-19 Pandemic Response

Considering the highly visible international response to the COVID-19 pandemic, what knowledge has been gained by states that may influence their perspective on developing, restarting, or strengthening an offensive BW program? History has proven that state and non-state groups gain critical insight by watching responses to natural disasters and deliberate attacks. The knowledge gained from observing responses may shape adversary future strategic and operational decisions to exploit identified vulnerabilities or strengths. We identified several lessons and potential results for consideration; however, it is not an exhaustive list. Our ideas are focused on state entities. Recognizing there is a degree of crossover, we believe the unique attributes of non-state entities warrant separate consideration.

Lesson #1 – A Highly Contagious Pathogen Can Rapidly Spread Throughout the Globe.

Result Deliberate deployment of a highly contagious lethal pathogen (HCLP) will also infect the deploying state; therefore, it is unlikely to be developed.

Result International response to deliberate deployment of an HCLP would likely include severe sanctions and punishment of the deploying state's leaders.

Result The deploying state could pre-vaccinate a particular segment of their people and allow enough of their population to become infected to deflect responsibility. This could support dominance on the other side of the pandemic. Even with a vaccine and inoculation infrastructure, deploying an HCLP is an all-or-none proposition; the spread may not be controllable.

Result The deploying state could develop therapies and other means to bolster immune response to lower internal vulnerability prior to deployment. The rapid development of capabilities could also be used to establish scientific dominance and exploited as a valuable commodity within the international community – infect the world clandestinely; then save the world publicly with a quickly developed, and highly profitable, therapeutic.

Result Developing BW capability may be an affordable and attainable deterrent for states willing to risk diseasing their citizens; loss of ally support; or international condemnation.

Lesson #2 – A Pandemic Can Cause Tremendous Social and Economic Disaster.

Result The ability to disrupt state socioeconomic structure is powerful and is likely to motivate state interest in HCLP as BW.

Result States focused on developing HCLP BW will weigh the challenges of controlling and restricting the range of infection with agent deployment. The pandemic demonstrates that the agent must spread easily to cause large-scale restrictions and fear. The risk of internal socioeconomic devastation may deter development of HCLP BW.

Lesson #3 – The Public Health Infrastructure of Most Developed Nations Is Not Adequate to Respond to a Pandemic.

Result HCLP BW agents may be considered as an initial step in an overall strategy, sufficiently weakening a country thus reducing their ability to respond to another form of aggression..

Result States may consider an offensive BW program as an economic way to create strong deterrence; it is relatively inexpensive to develop yet creates the power to destabilize nations.

Result HCLPs that have no prior vaccination implementation history will have a lengthier therapeutic development phase compared to novel strains of pathogens where vaccine development strategies are already in place. For example, the time to a vaccine for a novel influenza strain is likely much shorter due to multiple decades of vaccine development compared to coronaviruses where there is no vaccine history.

Lesson #4 – Misinformation Can Speed the Spread of a Contagion and Impact the Response in a Manner That Fosters Disease Propagation.

Result Incorporating strategic decisions, such as underreporting statistics and providing false information about disease transmission, can amplify the impact if deploying an HCLP BW.

Lesson #5 – Incorrect Data Skews the Models Used by Countries as a Foundation in Response Decision Making.

Result Deploying states report data that will knowingly skew the models to gain strategic advantage, manipulating initial responses until affected countries obtain enough internal data to correct input to models.

Result Deploying states may seek to develop cyber-intrusive means to manipulate models, to include intrusion of data reporting systems, data pools, or data analysis systems to gain advantages through the manipulation of response decisions.

Lesson #6 – Countries which are resilient, and willing to adhere to government restrictions, accept aegative economic consequences, and accept temporary loss of freedom in Order to Save Lives.

Result Given resiliency, states considering the use of HCLP BW will also develop ways to break altruistic spirit by creating fear of personal loss that people are willing to turn on fellow citizens.

Result States considering development, or use, of HCLP BW may retreat because international resilience and solidarity is stronger than previously believed.

Lesson #7 – Weaknesses and Strengths in Supply Chains Became Highly Visible in the COVID-19 Pandemic Response.

Result Deploying states may seek ways to disrupt the supply chain in order to further intensify the impact of an outbreak.

Result Deploying states may seek ways to leverage aspects of the supply chain that are under its control (e.g., critical lifesaving therapeutics, active pharmaceutical ingredients, and other medical countermeasures such as personal protective equipment).

Lesson #8 – Ships Are Especially Susceptible to the Spread of Highly Contagious Disease.

Result Deploying states may seek to disable naval defense by attacking naval vessels.

Result Deploying states may focus on cruise ships as an effective means of BW transmission.

Result Deploying states may focus on infecting crews on cargo ships in order to disrupt the international supply chain (e.g., medications, medical supplies, food distribution, and oil supply).

Lesson #9 – Pandemics Can Disrupt Election Processes.

Result States may develop an offensive HCLP BW capability for consideration as a means by which to shape international elections to favor the deploying state.

Lesson #10 – Pandemics can Affect Segments in Society in Divergent Ways.

Result Deploying states could exploit socioeconomic fissures resulting from the pandemic to create unrest and gain leverage in strategic countries.

What Might Be Next?

These ten lessons have the potential to renew interest in small-scale clandestine biological weapons programs by states within the BTWC regime. These programs would not be on the level of Soviet-style large-scale programs. Instead, they would consist of very small operations that could stand up in existing state facilities or be disguised within biopharmaceutical dual-use facilities. The goal of these programs would be to use non-attributable BW agents to disrupt a country's socioeconomic structure. No longer will the focus be to gain military supremacy by targeting soldiers; instead, the strategy will be to manipulate environments to the deploying the state's advantage.

It is unlikely that states would use traditional biological agents like those on the "Select Agent List"; rather, they will exploit new and emerging infectious diseases with properties suitable to create a pandemic. Further, efforts are unlikely to focus on genetically modifying an agent because this could lead to attribution or suspicion of intentional use. The COVID-19 pandemic publicly revealed microbial forensic capabilities through news about genetic modification assessments. To overcome the challenge of limiting, preventing, or controlling the damage to their own nation while creating the desired level of devastation externally, states may consider researching biological agents with seasonal cycles because they may have effective testing protocols and the greater outbreak plausibility provides advantages. Applying this concept to the COVID-19 pandemic, deployment in countries with high infectious disease burdens—to include endemic respirable diseases such as tuberculosis—could have exponentially worse health outcomes.

Attribution for this type of attack would be considerably difficult if a new or emerging infectious disease is employed, especially given how quickly our global economy supports the spread of disease and that many developed nations are not capable of effectively containing an outbreak. Therefore, a renewed interest in biological weapons, specifically non-traditional BW development, is a likely result of the COVID-19 pandemic. Further, the COVID-19 pandemic may have lowered the threshold for use of non-traditional BW when the target is socioeconomic and will create ambiguous circumstances that are inherently deniable.

The timing of a post-COVID-19 pandemic attack is an important consideration. Lessons learned by states affected from the pandemic are likely to improve responses to a new emerging pathogen in the near term. However, evidence in the global response to the COVID-19 pandemic indicates that lessons from the past may diminish over time and that states may struggle to maintain constant vigilance to respond to all threats. Assessment of timing in relationship to naturally occurring disease events may impact the effectiveness of deploying a non-traditional BW.

The aftermath of the COVID-19 pandemic will provide valuable information to states about the resiliency of a target and the types of outcomes a state can anticipate when opting to deploy an HCLP BW. It is important that the U.S. national security community is mindful of the knowledge that adversaries have gained from a specific U.S. response as well as from how our allies have reacted to the COVID-19 pandemic. History consistently conveys our enemies are learning from our actions to make calculated resource investment decisions to defeat the United States.

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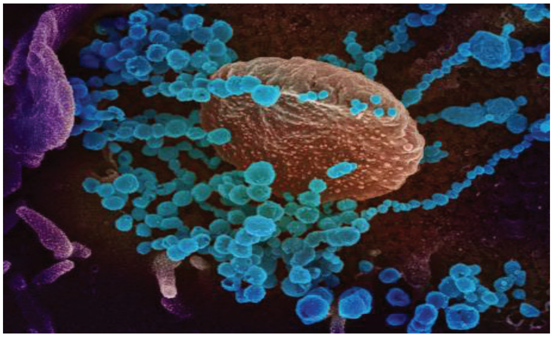


This scanning electron microscope image shows SARS-CoV-2 (round blue objects), the virus that causes COVID-19, emerging from the surface of cells cultured in the lab. The virus shown was isolated from a patient in the U.S. Image captured and colorized at NIAID's Rocky Mountain Laboratories (RML) in Hamilton, Montana.

Consideration of Carfentanil as a Weapon of Mass Destruction

LTC Mohamed B. Massaquoi
Joint Task Force North

Introduction

The National Security Strategy of the United States (NSS) lists Weapons of Mass Destruction (WMD) as the highest priority threat to the U.S. Homeland.[1] Within that threat, the NSS primarily focuses on conventional ballistic missile nuclear attacks from state actors, with additional consideration given to chemical weapons (CW) and biological weapons (BW) attacks by both state and non-state actors. As enemies of the United States actively seek new WMD technologies to harm America and its interests, some substances and agents are currently available whose lethality matches traditional WMDs but are not considered WMDs. One such substance is Carfentanil, an "ultra-potent" synthetic opioid that is available through illicit drug markets or easily synthesized privately.[2] Carfentanil is so potent that, in 2016, the Drug Enforcement Administration (DEA) issued a public warning stating that only properly trained and protected law enforcement personnel should handle substances suspected to be Carfentanil.[3] With an ongoing opioid crisis, coupled with persistent global WMD threats, there are sufficient grounds for attention to be given to a possible threat posed by Carfentanil.

The purpose of this research, then, is to investigate Carfentanil's potential for consideration as a WMD. A series of analysis based on Department of Defense (DOD) Joint Doctrine, U.S. national WMD policy, and the Organization for the Prohibition of Chemical Weapons (OPCW) Chemical Weapons Convention (CWC) will be used to accomplish this investigation: First, this study conducts a quantitative analysis of Carfentanil by its comparison to the characteristics of traditional chemical weapons using definitions and data from OPCW Fact Sheets, the CWC, and DOD Joint Publications. Next, a qualitative analysis will assess an actor's capability to develop Carfentanil into a WMD threat using DOD's Weapons of Mass Destruction Activity Continuum. Finally, this study uses a scenario analysis that applies a logic process to DOD's Joint Planning Process (JPP) to conceptualize the possible employment of Carfentanil as a WMD. These analyses will culminate in near-term recommendations for the Joint Force and U.S. policy makers in consideration of classifying Carfentanil as a WMD threat.

LTC Mohamed B. Massaquoi is the J5 Plans Chief at Joint Task Force North, in Fort Bliss, Texas. He has a B.S. in Liberal Arts from Excelsior College and an MBA in Financial Management from the Naval Postgraduate School. He was previously assigned as the Deputy G3 at 1st Armored Division, and Maneuver Planner at Combined Joint Operations Center Jordan. His email address is mohamed.b.massaquoi.mil@mail.mil.

Background

Carfentanil is a synthetic opioid developed initially in 1974 by Janssen Pharmaceutica to be a large animal tranquilizer.[4] Carfentanil is an analogue of Fentanyl, an analgesic used to treat chronic pain.[5] Fentanyl has an international designation as an essential drug for cancer pain management. In contrast, Carfentanil, whose commercial manufacture ceased in 2003, is now controlled by registration through the Drug Enforcement Agency (DEA)[6, 7] Carfentanil is highly potent; it is 10,000 times more potent than morphine and 100 times that of Fentanyl.[8] Two milligrams of Carfentanil accidentally ingested or contacting the skin can cause lethal respiratory arrest within minutes.[9] Naloxone (known commercially as Narcan) can reverse the effects of Carfentanil overdose, but multiple doses may be required to counteract the potency of Carfentanil.[10]

Like other synthetic opioids, Carfentanil is a highly sought after drug in illicit markets. Despite recent international efforts to curb access to its component substances (precursors), Carfentanil is still available illicitly, and producers add small amounts of the drug to heroin, marijuana, and cocaine to boost their potency.[11] This activity has resulted in an exponential rise in overdose deaths attributed to Carfentanil. In a 2018 Centers for Disease Control report, over 1,200 deaths were due to Carfentanil overdose between July 2016 and June 2017, with a 94% increase in deaths in the last six months of the study.[12] Reporting and statistics on Carfentanil seizures, however, are unreliable. When law enforcement agencies (LEAs) seize Fentanyl and its analogues, in most cases, the seizures are generally classified as "Fentanyl" without the specific analysis to determine if any of the drugs are Carfentanil.[13]

Carfentanil also shares the responsibility for the deaths of over 100 people in a single, deliberate incident. In October 2002, 33 terrorists, protesting Russia's occupation in Chechnya, stormed a theater in Moscow taking 800 hostages.[14] After three days of negotiations and skirmishes, Russian Spetznaz (Special Forces), used the theater's ventilation system to direct an unknown aerosol into the auditorium. According to first responder reports, 125 hostages, succumbed to unconsciousness and death without struggle within seconds.[15] While the Russian government never disclosed the substance released into the theater independent studies of survivors revealed that the aerosol contained at least two Fentanyl analogues including direct evidence of Carfentanil.[16] This public incident highlighted the possible employment of Carfentanil as an aerosol and demonstrated its lethal capacity at scale.

Quantitative Analysis of Carfentanil as a Chemical Weapon

The CWC defines CW in three parts: 1) toxic chemicals and their precursors; 2) munitions and devices used to kill or injure humans through their delivery of toxic chemicals and their precursors; and, 3) any equipment used to build those munitions and devices.[17] As one of 193 signatories of the CWC, the United States, and by extension the DOD, classifies chemical agents into four categories based on their physiological effects on the body: choking, blister, blood, and nerve agents. DOD further specifies chemical agents by type: traditional, non-traditional, toxic industrial, and riot control agents. Finally, both OPCW and DOD characterize CW by their rate of action, lethal amount, the form of dispersal, routes of entry, and persistency.[18] Based on these definitions and characteristics, a comparative model of the most lethal CW agents can be derived, as presented in Table 1.

CWC Chemical Weapon Definition						
Toxic Chemicals & Their Precursors				Munitions/Devices & Equipment		
DoD Chemical Weapon Specifications						
Category of Chemical		Chemical Agent Effects		Employment		
Chemical Weapon Characteristics						
Agent	Type	Rate of Action	Lethal Amount (mg, skin absorption)	Dispersal Form	Routes of Entry	Persistency
VX	Traditional (Nerve)	Rapid	10	Aerosol, dust, liquid, vapor	Skin	Very High
Soman (GD)	Traditional (Nerve)	Very Rapid	350	Aerosol, dust, liquid, vapor	Inhalation, Skin	Moderate
Sarin (GB)	Traditional (Nerve)	Very Rapid	1700	Aerosol, dust, liquid, vapor	Inhalation, Skin	Low

Table 1. Comparative Model of Chemical Weapons Agents. Sources: DOD & OPCW

There is a scientific precedent for comparing dissimilar WMD agents to CW agents. In "Toxins as Weapons of Mass Destruction," Dr. James Madsen, a Clinical Consultant at the United States Army Medical Research Institute of Chemical Defense, compares toxins (poisons produced by living organisms) to chemical and biological weapons across several characteristics, to include toxicity, route of entry, and persistence.[19] While Carfentanil was not expressly developed for use as a CW, the CWC allows for its consideration as a CW. Under the CWC's general-purpose criterion any toxic chemical or its precursors can be considered a CW depending on its intended purpose.[20] Since the CWC only defines which uses for toxic chemicals and their precursors are prohibited, considering Carfentanil as a chemical WMD would be appropriate should an actor choose to employ it to kill or injure others. Thus, the CW comparative model used earlier can include Carfentanil for analysis, as depicted in Table 2.

CWC Chemical Weapon Definition						
Toxic Chemicals & Their Precursors				Munitions/Devices & Equipment		
DoD Chemical Weapon Specifications						
Category of Chemical		Chemical Agent Effects		Employment		
Chemical Weapon Characteristics						
Agent	Type	Rate of Action	Lethal Amount (mg, skin absorption)	Dispersal Form	Routes of Entry	Persistency
VX	Traditional (Nerve)	Rapid	10	Aerosol, dust, liquid, vapor	Skin	Very High
Soman (GD)	Traditional (Nerve)	Very Rapid	350	Aerosol, dust, liquid, vapor	Inhalation, Skin	Moderate
Sarin (GB)	Traditional (Nerve)	Very Rapid	1700	Aerosol, dust, liquid, vapor	Inhalation, Skin	Low
Carfentanil	Nontraditional (Calmative)	Very Rapid	2	Aerosol, dust, liquid, vapor	Inhalation, Skin	High

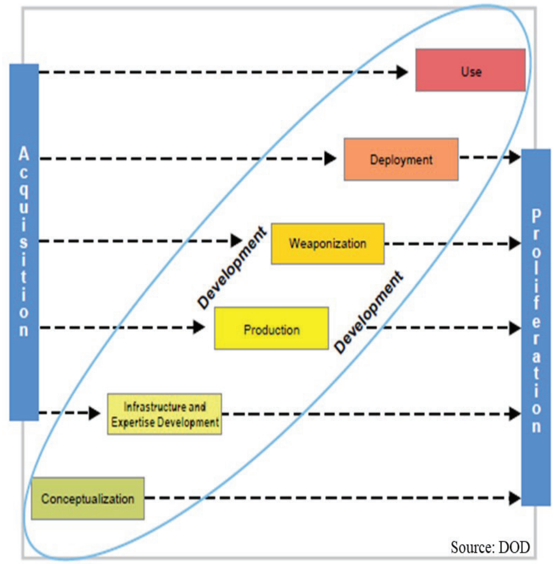
Table 2. Comparative Model of Chemical Weapons Agents and Carfentanil. Sources: DEA, DOD, & OPCW

By objective characteristics, Carfentanil is comparable to nerve CWs. Like Sarin and Soman, Carfentanil can be dispersed as an aerosol to achieve a very rapid rate of action (within minutes). Similar to VX, Carfentanil is very persistent, as evidenced by its residue being present on the clothing of survivors of the Russian theater hostage crisis two days after the siege ended.[21] Additionally, like all of the previously mentioned CW agents, a lethal dose of Carfentanil may be absorbed through the skin.

Carfentanil, however, is not a traditional CW agent (choking, blister, blood, or nerve). By DOD definition, since Carfentanil interferes with the proper function of the central nervous system (CNS), and abused as an illicit drug, it would be considered a nontraditional incapacitant.[22] Specifically, as a synthetic opioid analgesic Carfentanil is a calmative that depresses normal respiration. This respiratory depression is the primary physiological effect that causes death from Carfentanil overdose.[23] Therefore, by the CWC and DOD definitions, Carfentanil as a calmative (incapacitating) agent can be considered a chemical WMD.

Qualitative Analysis of Carfentanil as a WMD Threat

If Carfentanil is considered a CW, then it could also be considered a WMD threat. According to the DOD, a CW becomes a threat when intent joins the capability to develop CWs.[24] The NSS establishes the intent to develop WMDs to attack the United States and its interests. The NSS emphasizes that state and non-state actors are actively seeking weapons and technologies to attack the U.S. homeland.[25] For these actors, Carfentanil represents a ready opportunity to act against the United States. The capability to develop Carfentanil into a WMD can be established using DOD's WMD Activity Continuum, as seen in Figure 1:



(Figure 1. Weapons of Mass Destruction Activity Continuum.)

The WMD Activity Continuum is a process used to identify six key activities and decision points used by a state or non-state actor to develop and employ a WMD.[26] Carfentanil is unique in that the fluid nature of the international illicit drug trade could completely enable its acquisition and proliferation. Therefore, as they relate to Carfentanil's potential as a CW, activities on this continuum are either accelerated or made irrelevant due to the persistence of illicit activities:

Conceptualization (accelerated). Between the Russian theater hostage crisis (aerosolized Carfentanil), incidents of accidental skin contact by law enforcement officers (powdered Carfentanil), and formal studies testing aerosolized Carfentanil on lab animals, an actor does not have to be creative to conceptualize Carfentanil as a chemical WMD. Each incident involving a lethal dose of Carfentanil is a proof of concept of its potential use as a CW.

Infrastructure and Expertise Development (irrelevant). According to Dr. Munder Zagaar, a neuropharmacologist at Texas Southern University, minimal expertise or infrastructure is required to synthesize Carfentanil. Precursors are available on the internet and can be shipped to "clandestine" laboratories where a chemist can easily manufacture Carfentanil for illicit distribution and use.[27]

Production (irrelevant). The illicit drug trade has made Carfentanil and its precursors readily available via the internet. Should an actor want to forego synthesizing Carfentanil themselves, they could order one kilogram (2.2 pounds) online representing enough Carfentanil to kill 500,000 people.[28]

Weaponization (accelerated). As presented in the previous section of this study, Carfentanil, as normally synthesized, is as lethal as the most potent traditional nerve agents. As the former Assistant Secretary of Defense for Nuclear, Chemical and Biological Defense Programs, Andrew Weber stated simply of Carfentanil, "It's a weapon."[29]

Deployment (accelerated). The availability and lethality of Carfentanil blur the line between its conceptualization and possible deployment as a CW. As DOD notes, the pervasiveness of the availability of a chemical weapon makes attribution to a specific actor very difficult.[30] Thus, an actor, who now has little concern with being identified, needs only to decide how best to distribute an amount of Carfentanil to achieve a mass casualty, WMD effect .

Use (accelerated). Several countries, including the U.S., have investigated the use of calmative agents for riot control.[31] In the case of Carfentanil, its therapeutic index (the measure between a substance's therapeutic dose and toxic dose) is so narrow, that the risks of fatalities outweigh a beneficial outcome.[32] An actor pursuing this level of lethality, however, only needs a date and a location to deploy a Carfentanil weapon.

Placing Carfentanil within the context of the NSS and the DOD's WMD Activity Continuum makes the threat of its use as a CW more apparent. CWs, in general, provide a cost-effective means for an actor to attack a large, densely populated area.[33] Carfentanil, however, gives actors with ill-intent, not just the capability to develop, but ready access to an ultra-potent calmative agent through the illicit drug market. By these qualitative standards Carfentanil can be considered a WMD threat.

Discussion: Scenario Analysis of Carfentanil as a WMD

Despite the quantitative and qualitative analysis presented, three counterarguments can be made to support the assertion that Carfentanil should not be considered a chemical WMD. First, there are traditional CWs that are widely accessible through licit means. A primary example is the choking agent chlorine: using chemicals available in most households, an actor can produce the same chlorine gas used to lethal effect in World War I.[34] Secondly, while it is deadly in small amounts to humans, Carfentanil is still used and tightly regulated as a large animal tranquilizer. This practical and responsible use of Carfentanil could preclude its consideration as a WMD. Lastly, there is the general notion that any drug, in an excessive amount, can be poisonous to the human body. This argument supports the idea that even innocuous drugs (e.g., aspirin, ibuprofen) in sufficient amounts, could be weaponized.

The objective realities of the accessibility and potency of Carfentanil, however, negate these counterarguments. Unlike Carfentanil, CWs synthesized with legal precursors, require metric tons of component chemicals to achieve a "sufficiently large release."[35] Additionally, despite strict regulations limiting its availability, Carfentanil and its precursors are available illicitly, circumventing restrictions on its procurement. Finally, the amount, by weight, of over-the-counter analgesics necessary to achieve a lethal effect in one human, exceeds that of Carfentanil by several orders of magnitude (e.g., >5,000-10,000 mg of Ibuprofen, compared to 2 mg of Carfentanil).[36]

Context, therefore, is paramount in consideration of Carfentanil as a WMD: Conceptualizing circumstances that employ Carfentanil as a WMD is a necessary exercise to include in this research. The DOD uses scenarios to conceptualize an adversary's capabilities in its JPP.[37] Phenomena can be classified as a scenario using a six-question logical process offered by Matthew Spaniol and Nicholas Rowland:[38]

1) Are the events future-oriented?
2) Is there an external context?
3) Does the event have a narrative description?
4) Is the event plausibly possible?
5) Are the events part of a systemized set?
6) Are the events comparatively different?

As they apply to the development Carfentanil-related scenarios for the Joint Force, the answers to three of these questions are addressed in the Course of Action (COA) Analysis and Wargaming step of the JPP (Step 4). A narrative can be used to display wargaming results based on an adversary's decisions, which builds external context (e.g., identifying actors with the intent and capability to develop a CW to kill or harm others through illicit means).[39] Coordinating critical events of CW scenarios in a synchronization matrix (date, time, location for maximum effect), creates systemized sets of adversarial COAs. The three remaining questions of this logical process provide an opportunity for additional discussion on the threat of a Carfentanil CW attack:

Are the events future-oriented? The future is relative when considering the potential weaponization of Carfentanil. As established earlier in this research, the intent and capability to develop Carfentanil into a CW presently exist. Future-oriented scenarios of possible Carfentanil CW attacks are not only appropriate to consider, but necessary for contingency planning efforts.

Is the event plausibly possible? Table 3, below, highlights elements from previous terror attacks:

Element	1995 Tokyo Sarin Attack	1995 Oklahoma City Bombing	September 11th Attacks
Method of Attack	Dispersal of a privately synthesized nerve agent	Explosion of an independently manufactured, fertilizer-based bomb	Intenional collosion of multiple passenger aircraft into fixed terrain
Locations Targeted	Metropolitan subways	Government building	Government and commercial office buildings
Number of Attackers	Ten	Two	Nineteen
Casualties	13 fatalities; 1050 injured	168 fatalities; 680 injured	2,996 fatalities; 25,000 injured

(Table 3. Elements of Notable Terrorist Incidents.)

Before the execution of each of the events in the table above, possible plausibility would have been difficult to establish, particularly in the case of actors independently synthesizing sarin or attackers crashing passenger planes intentionally into skyscrapers. Constructing possible scenarios rooted in methods and techniques used in previous events lends weight to the further consideration of Carfentanil as a possible WMD.

Are the events comparatively different? Each event in Table 3 incorporates differences in locations targeted and the number of attackers. Using Carfentanil as a CW, these differences could result in a significant change in the magnitude of the number of lives lost. If an actor fully understands how, when, and where to employ a Carfentanil CW, any of these scenarios could dwarf the lethality of previous terrorist events.

Recommendations

Manage Risk Managing risk for a potential CW whose availability is very high, as in the case of Carfentanil, would be extremely difficult. A primary recommendation would be a whole of government approach to the consideration of Carfentanil as a WMD. This entire study was conducted using open source references and input from subject matter experts. A Whole-of-Government (WOG) approach could leverage shared concerns by improving Carfentanil interagency threat awareness (including, but not limited to DOD, Department of Justice [DOJ], and Department of Homeland Security [DHS]), counter threat activities, and focused contingency planning for a Carfentanil-related CW event.

Develop Consensus for Change As detailed in the qualitative analysis earlier, Carfentanil creates uncertainty in the WMD Activity Continuum. State and non-state actors alike have access to Carfentanil now: only planning a response to a possible Carfentanil attack acknowledges the danger without mitigating the threat itself. In this case, consensus should not be difficult to build. Government agencies are familiar with the narrow therapeutic index of calmative agents like Carfentanil through lessons learned from their search for effective riot control agents.[40] This knowledge must be parlayed into an active campaign to incorporate illicit calmative agents into broader WMD prevention and protection efforts.

Understand the Future The Carfentanil attack scenarios discussed earlier vividly demonstrate how past events can provide precedent and context for the future. However unlikely, religious fanatics synthesized sarin gas without government assistance, terrorists used commercial aircraft as ballistic missiles, and non-state actors could employ illicit Carfentanil as chemical WMD. Disablement (efforts to exploit and downgrade at-risk components of a WMD program) of weaponized Carfentanil should become a consideration, if not a priority, of defense contingency planners anticipating future threats from harmful state and non-state actors.[41]

Monitor Progress A recent study of synthetic opioid overdose deaths in Florida's Miami-Dade county revealed that of 134 deaths initially attributed to Fentanyl, Carfentanil caused 104 (77%) of those deaths.[42] In fact, according to Mr. Kim Keisling, a Senior Intelligence Analyst at Joint Task Force-North, the underreporting of synthetic opioid deaths, to include Carfentanil, may be a consequence of emergency overdose treatment: "In an effort to decrease the overdose stats and perceptions, mayors in 'crime-infested' cities require police and first responders to carry and administer naloxone. While this saves lives, it makes tabulation much more difficult."[43] In effect, while Carfentanil is known to be available illicitly, dedicated analysis to differentiate Fentanyl analogues are not routinely used.[44] The utility of such analytical specificity is apparent: By dedicating more resources to the detection of Carfentanil, trend and predictive analysis could be used to prevent the development of Carfentanil as a chemical WMD.

Conclusion

The goal of this research was to determine if Carfentanil, an "ultra-potent" drug readily available in illicit markets, could be considered a WMD threat. The conclusions of the three analyses conducted are:

1) In a quantitative analysis based on the CWC and DOD definitions, Carfentanil was determined to be a non-traditional calmative agent, with characteristics comparable to that of the deadliest traditional nerve agents.

2) Through a qualitative analysis scoped by the NSS and the DOD's WMD Activity Continuum, Carfentanil could be considered a WMD threat when the intent and the capability to develop a CW are determined.

3) In a scenario analysis that applied a six-question logic process to JPP COA analysis and wargaming, not only is a near-future incident involving a Carfentanil weapon "plausibly possible," but depending on the comparative differences in a given scenario (method of attack, time of attack, and number of attackers) the scale of the consequences of an attack could range from a relatively ineffective attempt to a catastrophic mass casualty event.

Based on the results of each of these analyses, Carfentanil should be considered a chemical WMD. The recommendations offered at the end of this research are an invitation, not just to the Joint Force, but to LEAs, members of academia, and policymakers to review, refine, or validate the conclusions made in this work. If the National Defense Strategy (NDS) is correct and the American Homeland truly is "no longer a sanctuary," then Carfentanil should be regarded as seriously as traditional chemical, biological, radiological, and nuclear WMD threats.[45]

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Operation Nittany Lion: Creative Mission Planning and Execution during the COVID-19 Pandemic

MAJ Stacey M. Yarborough, MAJ Mark S. Quint, and CPT Benjamin C. Troxell
Nuclear Disablement Team 3, 20th CBRNE Command

Nuclear Disablement Team 3 (NDT-3), assigned to 20th CBRNE Command in Aberdeen Proving Ground (APG), MD, is one of three NDTs in the US Army. These Soldiers are tasked with deploying and conducting radiological and nuclear assessments and characterization operations to locate, exploit and, when directed, disable nuclear or radiological WMD infrastructure.[1] Mission Essential Tasks (METs) and on-site activities support the overall NDT competency of site exploitation, which includes locating, securing, exploiting, reporting, and evacuating or destroying captured enemy material.[2]

The NDT mission is broad and complex, requiring a variety of unique training solutions to achieve mission objectives, ensure readiness, and maintain technical proficiency. Generally, NDT training exercises leverage partnerships with the Department of Energy (DoE) and use DoE National Laboratory facilities. However, during the COVID-19 pandemic, training at DoE facilities was constrained to protect their at-risk populations and minimize virus spread. Determined to maintain proficiency and deployability while adhering to COVID-19 restrictions, NDT-3 searched for solutions outside the norm.

MAJ Stacey M. Yarborough is the Deputy Team Chief for Nuclear Disablement Team 3 at the 20th CBRNE Command, in Aberdeen Proving Ground, MD. She has a B.A. in Biology from Bucknell University, a M.S. in Environmental Management from Webster University, and a M.S. in Nuclear Engineering from the University of Tennessee. She was previously assigned as a Chemical Officer in several different units. Her email address is stacey.m.yarborough.mil@mail.mil.

Major Mark S. Quint is the Secretary of the General Staff at the 20th CBRNE Command, in Aberdeen Proving Ground, MD. He has a B.S. in Mechanical Engineering from the United States Military Academy, and a M.S. Nuclear Engineering from the University of Tennessee. Most recently, he served as the Deputy Team Chief for Nuclear Disablement Team 3. He was previously assigned as a Field Artilleryman in several different units. His email address is mark.s.quint.mil@mail.mil.

CPT Benjamin C. Troxell is the Assistant Nuclear Operations Officer for Nuclear Disablement Team 3 at the 20th CBRNE Command, in Aberdeen Proving Ground, MD. He has a B.S. in Physics from the United States Military Academy at West Point and a M.S. in Nuclear Engineering from the University of Tennessee. He was previously assigned as an Infantry Officer in several different units. His email address is benjamin.c.troxell.mil@mail.mil.

Mission Planning and Preparation

Planning and preparation for Operation Nittany Lion began early in 2020, when unit leadership directed that the NDTs test their deployment discipline program to verify their ability to support a maneuver commander given limited notice. NDT-3, led by LTC Christina Dugan, accepted this challenge. An NDT consists of Soldiers of varying specialties, with a high level of formal education and experience: a Health Physicist Officer and NCO, CBRN Specialists, an EOD Officer, and Nuclear and Counter Weapons of Mass Destruction (FA 52) Officers, ranging from CPT to LTC. Due to the unique mission set of the NDTs, they must be ready to deploy on short notice. While the movement of a small team may appear to be an easy task, the NDT's robust equipment package, including multiple levels of specialized protective and detection equipment, increases deployment complexity.

Initial guidance dictated training exercises be conducted within 150 miles of APG, Maryland, in order to reduce exposure to COVID-19 from travel outside the local region. Based on this guidance, the team identified the Breazeale Nuclear Test Reactor on the Pennsylvania State University campus in State College, PA as a potential training location. As the country's first licensed, private nuclear reactor, the Breazeale Nuclear Reactor is used by students and faculty for a variety of research projects. However, for this exercise, NDT-3 treated the reactor and its infrastructure as an unknown target, with the mission of conducting reconnaissance, characterizing the facility, assessing its capabilities, and reporting findings to the commander of the Joint Task Force-Elimination (JTF-E).

To maximize training value, NDT-3 took on the additional challenge of executing an evaluated Deployment Readiness Exercise - Level III (DRE III). As outlined in AR 525-93, a DRE III is the highest level of evaluated deployment readiness and includes all tasks of lower-level DRE activities plus an evaluation of a unit's ability to conduct strategic movement by air (STRATAIR).[3] To fulfill this requirement, the 20th CBRNE CMD coordinated STRATAIR through Air Mobility Command (AMC). Availability of aircraft determined that the team would convoy to State College, PA, but return to APG after flying to Dover AFB, DE via STRATAIR from Williamsport Regional Airport, PA. The team required one C-17 Globemaster III to move all associated vehicles and equipment. In addition to organically assigned Soldiers, the NDT was reinforced with support personnel. For this training exercise, the team was accompanied by SPC Nester Hernandezgonzalez (wheeled vehicle mechanic), CW2 Aaron Kazer (20th CBRNE G4 mobility), SGM Gerald Hughes (20th CBRNE G3 Operations), and MAJ Joshua Mashl (20th CBRNE G35 Plans, Operations and Training).

Establishing Communications

A key training objective of the exercise was testing multiple communication platforms and establishing communications with the Joint Task Force-Elimination (JTF-E 20th CBRNE HQ). Operation Nittany Lion allowed NDT-3 to exercise its communications suite over a large portion of the electromagnetic spectrum. The regions of interest were High Frequency, Very High Frequency and Ultra High Frequency. NDTs are equipped with the capability to utilize each of these regions to take advantage of each regions' strengths. At least one communication system was employed per region highlighting the extensive communications suite of the NDTs. FA 52s, chemical, and EOD Soldiers must learn to employ all systems in addition to their primary mission.

The first and lowest energy region, HF, enabled over the horizon communication. The benefit of this communication system was it enabled NDT-3 to communicate with its headquarters at APG, MD, while deployed to State College, PA, 210 km without the use of satellites, which may not be accessible after a nuclear detonation.

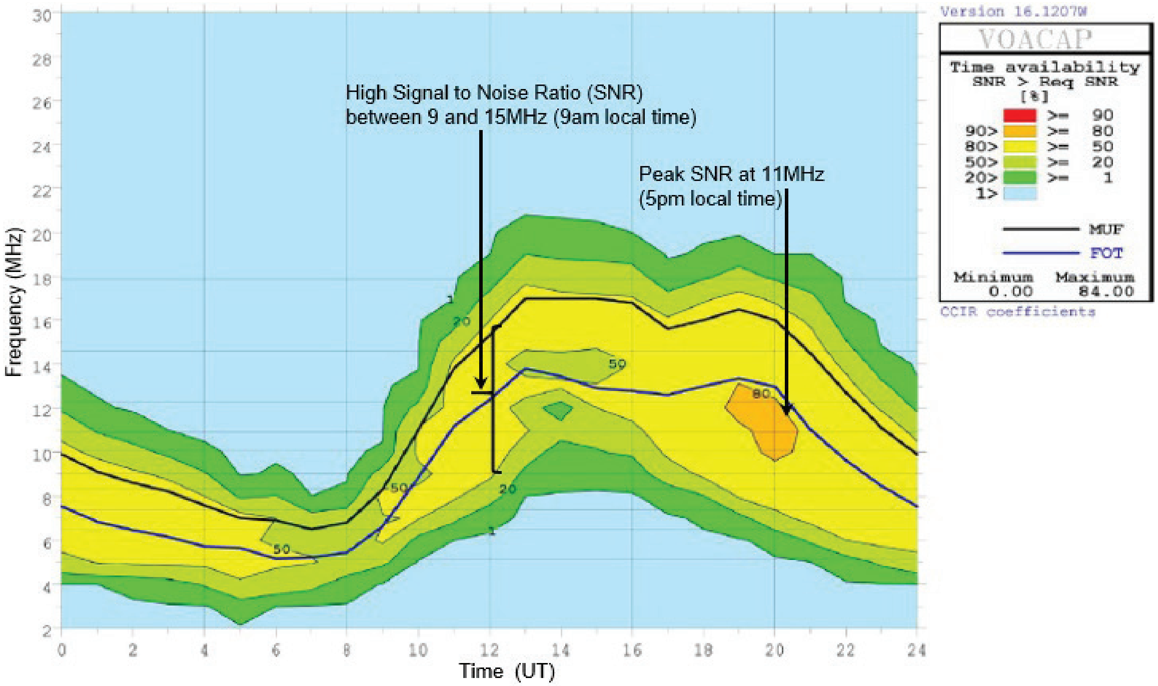


Figure 1. Signal to Noise Ratio (SNR) as a Function of Frequency in MHz vs. Time of Day[4]

HF is directional and requires an external power source to communicate over hundreds to thousands of kilometers. The result is a highly resilient, extremely long distance means of communication. MAJ Nicholas Antonio and CPT Benjamin Troxell transmitted from Penn State University while CPT Adam Hunter and SFC Anthony Paolucci established the transmission site at APG. Both teams utilized the AN/PRC-160(V) radio, 150-watt power supply, and a V-shaped dipole antenna at their respective sites.

The primary means of communication, the VHF band, was utilized for internal convoy operations and during site exploitation. VHF communication platforms propagate mainly by line-of-sight (LOS), hence are limited in their application. However, the benefit of VHF is less atmospheric noise and interference from electric equipment than HF. The result is VHF can be used at all times of day for communication if LOS is not an issue.

The primary radio used for VHF was the AN/PRC-148, also known as the MBITR. The Motorola SRX2200 was a secondary method of LOS communication utilized during convoy operations and within the site for characterization and exploitation. However, the Motorola SRX2200 falls into the low end of UHF communication. The UHF range again is limited to LOS communication and unlike HF has little to no reflection from the ionosphere. The main benefit of UHF communication is its ability to penetrate foliage and buildings. As such, it was utilized at Penn State University, establishing an onsite Wi-Fi network.

By employing a Wi-Fi network, the team remotely collected and monitored sensors within the facility without the need of continuous exposure of an individual to a radiation field. This system requires network node emplacement. As a form of nonionizing radiation, any facility shielded against gamma-radiation will be unreachable by UHF. The primary router utilized for UHF was the Rajant BreadCrumb.

As with all military operations, communication is key. Given the unique mission set of the NDTs, it is essential that all communications systems be exercised during each training event, to continue to improve capabilities. Given that the NDTs' missions are highly integrated with the Department of Energy, and other stakeholders, the communications plan is continually evaluated so that voice and data communications with all agencies is possible. As new equipment and technologies emerge, the NDTs continue to test potential platforms and refine their communications plan.

Site Entry and Characterization

Picture 1. NDT Command Post

With the establishment of a small command post (CP) outside the reactor building, the team began on-site operations. The NDT CP consisted of a central tent for operations, a dress-out area, and a decontamination line. Before operations began, the team went through a detailed checklist and setup procedures such as topping off tanks if needed. As each team member staged their personal protective equipment, they also checked all detectors for proper calibration and sufficient power levels. Radiation background spectra were taken with each detector. All team members underwent basic medical monitoring in addition to COVID-19 temperature scans, establishing a medical baseline. Anyone donning a SCBA (Self-Contained Breathing Apparatus) or other respirator received home-station training and a required occupational health physical, in addition to post-use medical monitoring.

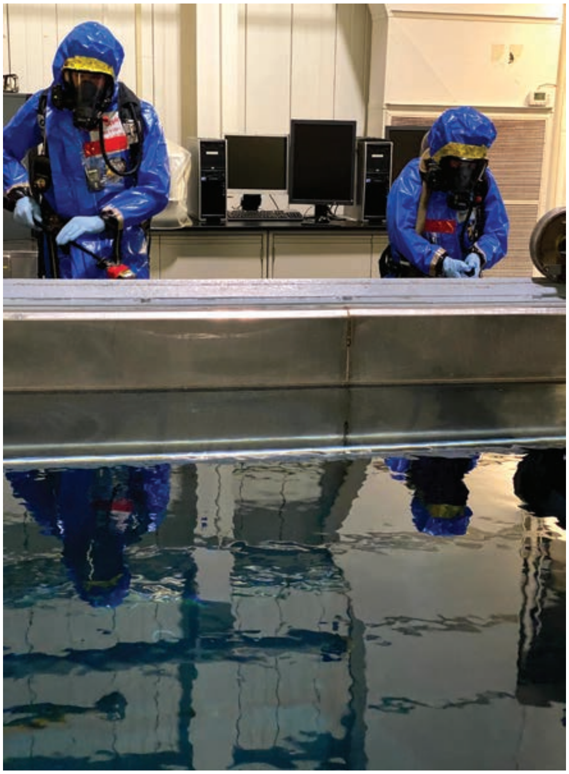
In the mission briefing, following equipment checks, the commander's and team chief's guidance is issued, including known information, and the designation of entry and rescue teams. It was determined beforehand all teams would enter wearing Level A or B protective suits, with SCBA, for training purposes. Following each team's debriefing, the team will reassess mission requirements based on the recently gathered data. Air quality concerns, significant safety hazards, and greater fidelity of site assessment drives the mission timeline, the number of required follow-on teams, the ability to sample and disable.

Picture 2. Initial Entry Team Dress Out

Site exploitation began with external radiation readings and visual inspection of the facility's exterior. The first team designated to enter the facility was the Initial Entry Team (IET), consisting of CPT Derek Whipkey, EOD, and SPC Benjamin Mou, 74D. The IET's role in site exploitation is to conduct an all-hazards assessment of the interior and exterior of the building. This includes hazards that may prevent reducing protection levels, such as air quality concerns (such as HF gas) and areas of elevated radiation. The IET carries multiple detectors to address the multiple potential hazards.

For this exercise, the IET carried two Honeywell MultiRAE Pro Gas Monitors, two Thermo-Scientific B20-ER contamination monitors (alpha, beta, and gamma), the Thermo-Scientific PRD-ER gamma radiation monitor, the FLIR identiFINDER (neutron and isotope identification), the Thermo-Scientific Rad Eye GN+ radiation detector (gamma and neutron), and a digital camera. In addition to detection equipment, both IET members wore electronic personal dosimeters (EPD), Motorola Radios, and Level-A protective suits with SCBA. The initial readings and assessment of this team drove the priorities of the follow-on characterization teams.

The IET surveyed the Breazeale Reactor's main building using gamma and neutron radiation detectors, and the MultiRAE gas monitor. Outside of the main reactor building, the IET noted elevated gamma radiation levels. Using the FLIR identiFINDER, the team recorded a presumptive identification of Co-60. Entering the building on its lower level, the IET covered both floors of the building. In the first room they observed two shielded hot cells with electro-mechanical manipulators, as well as a large white container. The container appeared to be primarily shielding around a small tube, and produced signature gamma rays of 1173 and 1332 keV, indicative of a significant Co-60 source. Another area of interest was a clear pool of water of significant depth which housed a Co-60 gamma radiation signature. After departing this room, the IET ascended stairs to the large Training, Research, Isotopes, General Atomics (TRIGA) reactor pool. The team recorded detectable, but not concerning, levels of gamma and neutron radiation. They did not detect any air quality concerns, or high radiation areas in the facility. All areas were clean, organized, and well-marked with general safety and radiation signs.



Picture 3. Characterization of Reactor Pool

Following their return, the IET debriefed their findings. The explored area was then divided into sections and assigned to characterization teams. Each characterization team consisted of two FA-52 officers responsible for collecting detailed measurements and possible information of value within their assigned zone. Given the weight of the carried equipment, 70°F weather, and the SCBA, each team was estimated to have 30 to 45 minutes to observe their portion of the building recording as much critical information as possible.

MAJ John Peters and CPT Benjamin Troxell made up the first characterization team. Immediately upon entry, the team identified the two hot cells. MAJ Peters and CPT Troxell spent approximately 30 minutes collecting swab samples and conducting gamma spectroscopy of the hot cells and the surroundings. The team carried two EPDs, two Thermo-Scientific Rad Eye GN+, two Thermo-Scientific B20-ER, and one FLIR identiFINDER.

The FLIR IdentiFINDER was used to collect device spectra off of a dry Co-60 irradiator discovered by the initial entry team in proximity to the hot cells. Despite their name, the hot cells did not emanate any radiation above background. Instead, the only source of radiation within the immediate area was the dry Co-60 irradiator which gave off a surface dose rate of approximately 0.30 millirem per hour. The team collected swab samples of the hot cells and surroundings in addition to collecting the spectra of the irradiator. These swab samples were analyzed after the team exited the facility. None of the samples collected exhibited radioactive material - a sign of good housekeeping within the facility.

After characterization of the hot cells, the team moved upstairs. They entered an office space with various experiment notes. Along the way they noticed a thick concrete wall which they identified as the reactor pool. At this point the team was running low on air and after 40 minutes within the facility they exited to report their findings. After being debriefed, MAJ Mark Quint and MAJ Stacey Yarborough prepared to enter the facility as the second characterization team.

Picture 4. Characterization of Reactor Pool with Ortec Detective-DX 100T,

Once the second characterization team entered the facility, they moved immediately to the upper floor, to characterize the main reactor pool and reactor control room. Using the Ortec Detective-DX 100T, the team collected a spectrum of gamma-ray energies near the pool. Based on the spectrum peaks, the Ortec Detective gave a presumptive identification of low enriched uranium (LEU).

MAJ Quint and MAJ Yarborough detected neutrons around the pool, and from water circulation pipes. Besides the pool, many experimental setups were observed. One barrel of interest was marked Special Nuclear Material (SNM). Within the pool, along the inner walls, metal rods in storage racks were observed, though no plutonium signature was detected. The reactor pool water was very clear, indicating very good water circulation and filtering. Inside the control room, all reactor operations appeared normal. Reactor power indicators displayed 200 kilowatts thermal. After finishing the room sketch and notes, characterization team two returned for debriefing.

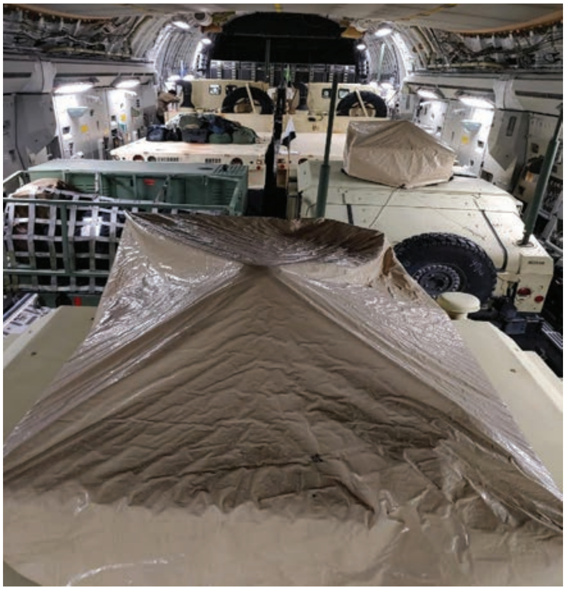
After each characterization team collects data and pictures, the NDT conducts an assessment to determine the potential activities they observed. This is significant to determine if any illicit activities are being conducted and assist with intelligence collection. For the Breazeale Nuclear Reactor, NDT-3 assessed a potential for Pu-239 breeding due to on-site SNM storage, radiochemistry labs and hot cells; however, no direct observables to say this is occurring. The team submitted a site exploitation report to JTF-E.

In order to provide an assessment on the team's site characterization report, the team is able to tour the facility and compare their findings. The Director of the Radiation Science and Engineering Center (RSEC), and the Associate Director for Operations and Associate Research, facilitated the tour. The group toured the reactor control room and pool, and were permitted to observe a reactor pulse. The design and specifics of a TRIGA reactor make it one of the few in the world where reactivity can be added, making the reactor prompt supercritical and emitting a blue flash, without risk of core meltdown or other safety issues. The reactor core, which first went critical in 1955, is located in a 24-foot pool with approximately 71,000 gallons of demineralized water and features a pneumatic transfer system.[5] Unique to the Breazeale Reactor is its ability to move its core, while offline, between two sections of the pool, allowing for a greater variety of research to be conducted, but of note is also a proliferation concern. In addition to the TRIGA reactor, the Breazeale Reactor building has an irradiator pool and a dry irradiator, each with a Co-60 source, for gamma radiation experiments.[6] The hot cells, observed by each team upon entry, were not currently in use due to planned refurbishment. When operating, the RSEC Hot Cell Laboratory (HCL) is capable of handling 100 to 350 curies of activity, and direct transfer from the reactor pool and between the cells.7 The Breazeale reactor is truly unique in its design and capabilities.

Picture 5. Breazeale Reactor Tour

Exercise Transportation

Once completed, the team packed up and prepared for the final part of the exercise, the flight to Dover AFB. Movement to Penn State University campus was conducted via ground convoy. The team safely and successfully convoyed from APG, MD, to Williamsport, PA, on September 14, 2020. Thanks to support from the PA Air National Guard, NDT-3 was permitted to secure all military equipment within the gates of the 193rd Air Operations Group air station in State College, PA. In addition, the PA ARNG Field Maintenance Shop #29 provided ground recovery capabilities while the convoy traversed PA. NDT-2 from APG, MD, provided ground recovery capabilities while traversing Maryland. The following day the team established their CP at Penn State's Breazeale Nuclear Reactor. The convoy tested both the personnel and administrative capacity of the 20th CBRNE. COVID-19 tests, rehearsals, recovery team coordination, and battle tracking were all part of the lead up to the seven-hour convoy that challenged the vehicles and drivers in a way that could not have been tested otherwise.



Picture 6. C-17 Loadout

After completing their assessment, the team conducted a fifty-mile convoy from State College, PA to Williamsport, PA for their return flight to Dover, DE. The NDT and the US Air Force Joint Inspection (J/I) team certified the vehicles and equipment for air load. On September 18th, the C-17 was loaded and redeployed to Dover AFB, DE. The highlight of this phase of the operation was the load out of the C-17 in less than 90 minutes. A large part of the success of the STRATAIR movement is attributed to the C-17 crew from Hawaii and the support provided by the ramp operations personnel assigned to the 436th Aerial Port Squadron.

Lessons Learned

This exercise highlights the unique opportunity an NDT position presents to FA-52 officers, as it is a position within the functional area with an operational mission. Because NDT officers must be able address novel problems and prepare for unexpected events, NDT Soldiers are at the forefront of standard operating procedure (SOP) and doctrine development. Exercises such as Operation Nittany Lion best enable the NDTs to accomplish this daunting task.

Operation Nittany Lion emphasized the importance of pre-inspections and prior coordination. The team's success in passing the Air Force Joint Inspection (J/I) is directly attributable to the pre-inspections conducted by APG's installation transportation office, the support of AMC, and the 20th CBRNE G4. Since the use of STRATAIR requires officers trained in the transportation of hazardous materials, air load planning, and unit movement, the exercise emphasized the importance of depth in additional duties to eliminate single points of failure. The exercise highlighted the strengths and shortcomings in the NDT-3 initial entry and characterization SOPs and led to their refinement. With the exercise of the communications platforms, NDT-3 was also able to refine their communications plan and reporting process in accordance with our higher command's guidance. Overall, the training exercise trained new team members, evaluated SOPs, increased the team's readiness, and improved the team's overall confidence in conducting short-notice deployments.

Conclusion

The exercise concluded the following morning after a 2-hour convoy back to APG, MD, and a welcome home picnic hosted by the unit chaplain. Overall, the mission was successful, and all members of NDT-3 demonstrated they and the 20th CBRNE Command are prepared to conduct a limited-notice deployment and characterize an unknown nuclear facility. While COVID-19 cancelled or significantly altered many military training events, what units could accomplish within guidelines had an enormous value. Given the mission of the NDT, they can now, with confidence, state that they are ready to deploy globally on short notice. Additionally, the teams identified areas of improvement in order to prepare faster and easier in the future. "Operation Nittany Lion provided NDT-3 realistic mission-focused training," stated LTC Christina Dugan, "The team's readiness multiplied through increasing our deployment repetitions and synchronizing with our Air Force partners." The success of Operation Nittany Lion cannot be attributed to any one person or organization; it is an example of exceptional teamwork across a vast network of professionals, all working together to accomplish a mission.

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Development of a Criticality Safety Standard Operating Procedure for Nuclear Disablement Teams

MAJ Richard E. Shawger
United States Army, 20th CBRNE Command

Introduction

The Nuclear Disablement Teams' (NDT) mission is to characterize, sample, and disable nuclear infrastructure. This mission is vast and complex, requiring an array of niche, technical knowledge and hands-on experience in many areas throughout the nuclear fuel cycle. The sampling and handling of fissile materials is at the crux of this mission. Thus, criticality safety poses one of the greatest challenges for the NDTs in accomplishing their mission safely. The history of known criticality accidents provides enough evidence to warrant extreme caution when conducting operations with fissile materials. In order to mitigate the risk of a criticality accident, the Department of Energy Nuclear Criticality Safety Program's Criticality Safety Engineer (CSE) Course provided the required knowledge to educate the NDTs on criticality safety. As a result, an operational criticality safety Standard Operating Procedure (SOP) was developed.

Education

The CSE Course consists of two weeks of training: a week of education and a week of hands-on training in criticality safety. Participants must pass a test each week with a score of 80% or higher in order to receive their CSE Certificate. The first week of the CSE Course provides in depth study of criticality safety to include American National Standards Institute (ANSI) and American Nuclear Society (ANS) criticality safety policy, ANSI/ANS subcritical limits, and methods of making subcritical calculations. The first week of training culminates with the development of a criticality safety evaluation, similar to a SOP, which outlines the engineering and administrative controls necessary to keep a fissile material operation subcritical. During the second week, participants conduct criticality experiments in accordance with criticality safety evaluations.

The main takeaway from the CSE Course is that a criticality safety evaluation must ensure a process remains subcritical under not only normal operating conditions, but also any and all credible, abnormal conditions. Thus, the worst-case credible abnormal conditions drive subcritical limits. In order to ensure these conditions are met, the criticality safety evaluation's subcritical limits and procedures must be bounded by experimental data and/or validated by a criticality computer code like Monte Carlo N-Particle (MCNP6) transport code[1].

Major Richard Shawger is a Nuclear Operations Officer of the Nuclear Disablement Teams at the 20th CBRNE Command, U.S. Army, at Aberdeen Proving Ground, MD. He has a B.S. in Mathematics from Muskingum University and a M.S. in Nuclear Engineering from The Ohio State University. He was previously assigned as the Course Director for NE300: Fundamentals of Nuclear Engineering at the United States Military Academy. His email address is richard.e.shawger.mil@mail.mil.

Scope of the NDT Criticality Safety SOP

In the course of executing the NDT mission, the greatest risk of a criticality accident is during the various phases of sample collection. While the specifics of a NDT mission is largely unknown prior to entry, the NDTs anticipate taking samples from enrichment, reprocessing, fissile material storage, fissile material fabrication, or experimental lab facilities. Within these facilities solid and/or solution samples may be taken. Thus, the SOP focuses on likely sampling scenarios, providing subcritical limits, administrative and engineering controls, and sampling procedures for criticality safety during missions. This article only focuses on the development of the subcritical limits for these operations:

- Approaching fissile materials
- Storing fissile material samples in a Subcritical Array (SCA)
- Sampling fissile materials
- Transporting fissile materials
- Packaging fissile materials for shipment

Facts and Assumptions in the SOP

The foundation of the SOP is the single-parameter subcritical limits for uniform aqueous solutions or metal units as established by ANSI/ANS[2]. It is important to note these limits assume full water reflection.

Parameter	Subcritical limit for fissile solute				
	$^{233}UO_2F_2$ [15]	$^{233}UO_2(NO_3)_2$ [15]	$^{235}UO_2F_2$ [16]	$^{235}UO_2(NO_3)_2$ [16]	$^{239}Pu(NO_3)_4$ [16]
Mass of fissile nuclide (kg)	0.54	0.55	0.76	0.78	0.48
Diameter of cylinder of solution (cm)	10.5	11.7	13.7	14.4	15.4
Thickness of slab of solution (cm)	2.5	3.1	4.4	4.9	5.5
Volume of solution (L)	2.8	3.6	5.5	6.2	7.3
Concentration of fissile nuclide (g/L)	10.8	10.8	11.6	11.6	7.3
Atomic ratio of hydrogen to fissile nuclide[1)]	2390	2390	2250	2250	3630
Areal density of fissile nuclide (g/cm^2)	0.35	0.35	0.40	0.40	0.25

1) Lower limit.

Table 1: Single-parameter subcritical limits for uniform aqueous solutions of fissile nuclides. Extracted from American National Standard ANSI/ANS-8.1-2014 (R2018) with permission of the publisher the American Nuclear Society.

Parameter	Subcritical limits for		
	^{233}U [15]	^{235}U [16]	^{239}Pu [17]
Mass of fissile nuclide (kg)	6.0	20.1	5.0
Cylinder diameter (cm)	4.5	7.3	4.4
Slab thickness (cm)	0.38	1.3	0.65
Uranium enrichment (wt% ^{235}U)	–	5.0	–
Maximum density for which mass and dimension limits are valid (g/cm^3)	18.65	18.81	19.82

Table 2: Single-parameter subcritical limits for metal units. Extracted from American National Standard ANSI/ANS-8.1-2014 (R2018) with permission of the publisher the American Nuclear Society.

These limits are useful when approaching a potential fissile material in which the mass, geometry, or volume is known or can be easily determined through measurement. However, the NDTs cannot anticipate or know the required details about a sample for safe subcritical limits such as: the fissile isotope, the enrichment of the fissile isotope, the concentration of the fissile isotope in a solution, or the mass of the sample. Therefore, the SOP used the most conservative subcritical limit available for solid or liquid samples. Thus, the following assumptions were made to develop the SOP:

- The NDTs will not encounter ^{233}U.
- All metal is considered to be α-phase, 100% ^{239}Pu with a density of 19.82 g/cm^3 [See endnote[3]]
- All metal to be sampled is considered to be spherical in shape and fully water reflected.
- All solutions are considered to be, $^{235}UO_2F_2$, spherical in shape, and fully water reflected.
- The hand calculation formula to determine the sample center-to-center spacing for the most dangerous criticality scenario is the Surface Density Method[4]. This method assumes the SCA is a two-dimensional infinite array, which provides a conservative spacing limit. MCNP6 validated all SCA calculations.
- The SCA will be no larger than a 5 x 5 array = 25 samples.

The Development of Subcritical Limits in the SOP

With these assumptions made, NDT missions were analyzed with respect to the parameters that affect criticality to develop the subcritical limits for the various phases of sample collection. These criticality parameters are: mass, absorption, geometry, interaction, concentration/density, moderation, enrichment, reflection, and volume (MAGICMERV). The only mission in which the subcritical limits could be determined easily without calculation was approaching fissile materials. This was possible by using standoff measurement techniques to determine a single criticality parameter of a fissile material and using the single-parameter subcritical limits previously mentioned.

The interaction parameter with regard to the mission of storing samples in a SCA was complex, required significant modeling, and was paramount in determining all other sample limits that would remain subcritical under both normal and credible, abnormal conditions. Under normal conditions the sample team only collects and transports one sample at a time. This eliminates the opportunity of two subcritical samples interacting and becoming supercritical. Thus, as seen in Figure 1, the 5 kg of ^{239}Pu seems like a reasonable subcritical mass limit for fissile metals. However, under the credible, abnormal condition of a person tripping and/or dropping a sample in the SCA where it lands next to another sample, will the two samples together remain subcritical? No, they will not. Thus, the subcritical mass limit for a metal sample must be less than 5kg. Hence, the sample limit, for the SCA, determines the subcritical limits for all other missions except approaching a fissile material.

MCNP6 determined the mass of a single sphere of ^{239}Pu to be 3 kg, where two identical, touching spheres, fully reflected remained subcritical. The Surface Density Method, as seen below, was used to determine the subcritical center-to-center spacing between samples in the SCA.

$$d\ (cm) = \sqrt{\frac{nm}{.54\sigma_0(1-1.37f)}}$$

σ₀ = *density of fissile material*infinite reflected slab of fissile material*

f = *mass fraction<.73: ratio of the fissile mass of a unit in the array to the crtical mass of the unreflected sphere of the same fissile material*

n = *1;thus,a 2 dimensional criticality safe array*

m = *fissile material mass per array unit (g)*

Thus, substituting the values for a 3kg sphere of ^{239}Pu, the spacing is found to be:

$$\boldsymbol{\sigma_0} = 19.82\frac{g}{cm^3} * .82\ cm^5$$

$$\boldsymbol{f} = \frac{3000\ g}{10000\ g^6}$$

$$\boldsymbol{n} = 1$$

$$\boldsymbol{m} = 3000\ g$$

$$\boldsymbol{d}\ (cm) = \sqrt{\frac{1(3000)}{.54(.82)(19.82)\left(1-1.37\left(\frac{3000}{10000}\right)\right)}} \approx 24\ cm$$

$$\boldsymbol{d = 24cm\ x\ 2 \sim 50\ cm}$$

The calculated center-to-center spacing was doubled for additional safety by limiting the interactions between samples. It also made the spacing more practical to walk between in the array and made the array spacing an easy number to remember. MCNP6 modeled the SCA geometry with 50 cm center-to-center spacing and calculated the SCA's multiplication factor, k-effective (k_{eff}) = .72877 +/- .00060.

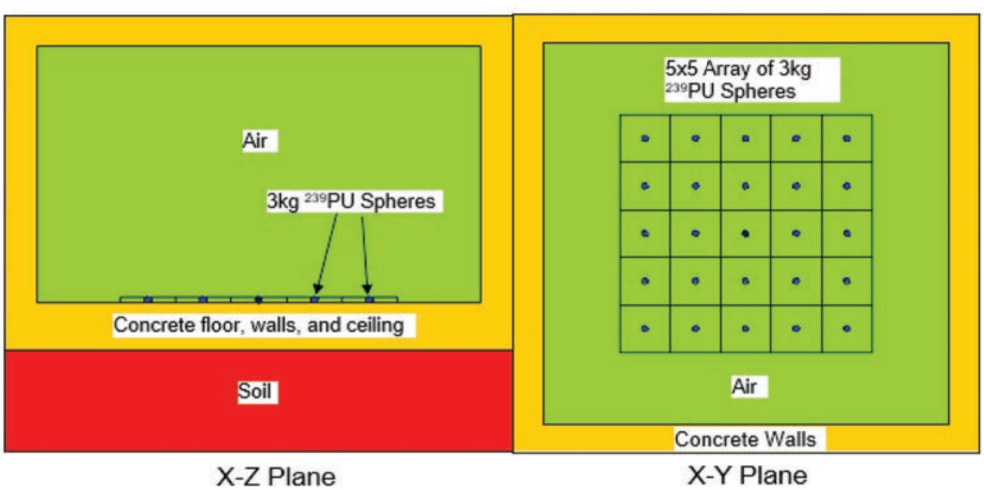

Figure 1: MCNP6 model of full SCA

The most dangerous scenario under normal operating conditions occurs in a full array with a person retrieving the center sample. A crouching person was modeled as a 60cm x 60cm x 100cm rectangular prism. This provides much more reflection and moderation than an actual human, making the estimate prudent. The resulting k_{eff} = .84561 +/- .00060. As expected, a person in the SCA significantly increased k_{eff}.

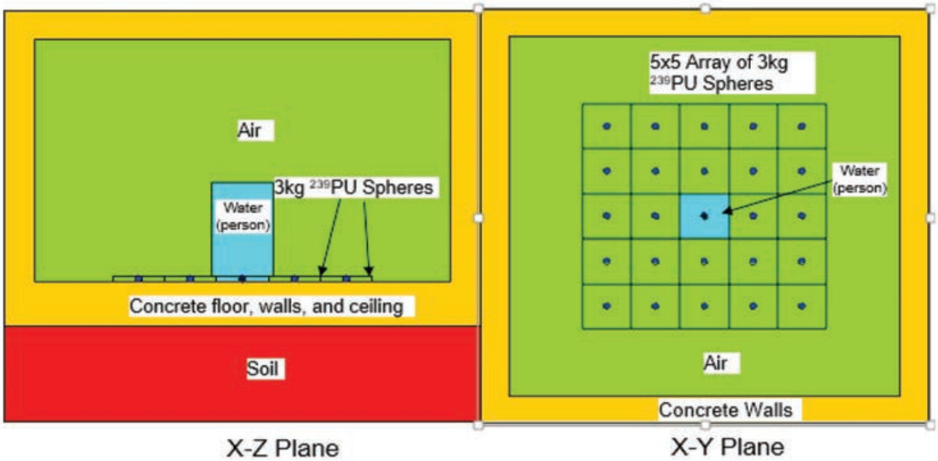

Figure 2: MCNP6 model of person retrieving center sample from a full SCA

Therefore, to see if spacing of the array adequately neutralizes the interaction between samples, the full array was flooded with water. This resulted in the same k_{eff} =.84561+/- .00091, but with only slightly greater uncertainty. This clearly demonstrated that the array spacing essentially isolates each sample from another and validated that the SCA remains subcritical under normal operating conditions.

In order for the subcritical limits to be finalized, the SCA had to be tested under credible, abnormal conditions. The most dangerous credible, abnormal condition occurs in a full array, when a person retrieves the center sample when it has been dropped next to an adjacent sample. Thus, the two sphere system is fully reflected and k_{eff} increases to .96444 +/- .00097, which is below the k_{eff} = .97891 of the upper subcritical limit for fully reflected ^{239}Pu metal[7]. Therefore, the subcritical limits under credible, abnormal conditions were validated. Once again, the array was flooded with water, under credible, abnormal conditions, which yielded a k_{eff}=.96433+/- .00103, demonstrating and reinforcing the safety of the subcritical mass limit and the 50 cm spacing of SCA.

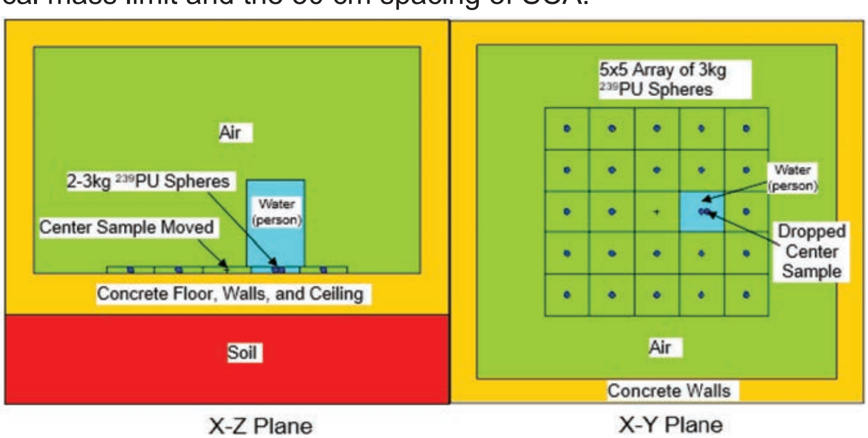

Figure 3: MCNP6 model of credible, abnormal condition: human retrieving dropped sample in full SCA

With the validation of the SCA remaining subcritical under normal and credible, abnormal conditions the subcritical limits for solid samples could be finalized. For liquid samples, a subcritical limit was determined such that the SCA spacing of 50 cm would be valid for any combination of metal or liquid samples. The validation of the liquid volume subcritical limit and SCA spacing for any sample was similar to the analysis for determining the solid subcritical limits. The final subcritical limits of the SOP are shown below.

- Metal Mass limit (during approach): 5.0 kg (250 cm³) [See endnote[8]]
- Metal Mass limit (sample): 3.0 kg (150 cm³)
- Max Solution Volume limit (during approach): 5.5 l [See endnote[9]]
- Max Solution Volume limit (sample): 1.0 l
- Solution cylinder max diameter: 13.7 cm (5.3 in) [See endnote[10]]
- Solution slab maximum thickness: 4.4 cm (1.7 in) [See endnote[11]]
- The subcritical center to center spacing for the sample storage SCA is 50 cm.

In conclusion, the NDT Criticality Safety SOP provides the NDTs with the necessary subcritical limits, controls, and procedures to safely approach, collect, transport, store, and package fissile material samples in order to accomplish its mission of assessing, characterizing, and disabling nuclear infrastructure. The SOP paired with training increases the mission readiness of the 20th CBRNE Command's NDTs.

Notes

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A Department of Energy Analyst, places ground samples into a oven during the Prominent Hunt 18-1 exercise at Burbank, Ca. (U.S. Army photo by Spc. Joseph Friend)

A Survey of Portable Counter-Proliferation Technologies”

CPT Grant V. Mallalieu
Eighth United States Army

Introduction

Portable counter-proliferation technologies have evolved from simple sensors that detect the presence or absence of nuclear material to more sophisticated devices that can determine the mass, isotopic composition, enrichment, and even geometry of any nuclear material in question. This article addresses only portable devices and their relationship to other counter-proliferation measures, including fixed sensors and tamper-indicating enclosures that also ensure that nuclear facilities comply with international law.1 Equally important are stationary devices which are installed throughout the world at such critical junctures as airports, border crossings, and bridges. However, because the international community has charged the International Atomic Energy Agency (IAEA) with the duty to conduct in situ assessments of the 1968 Non-Proliferation Treaty (NPT) signatory states' nuclear facilities, two mobile technologies are of particular interest in the global counter-proliferation regime. This article will provide some background on the diplomatic and regulatory framework within which portable counter-proliferation technologies are employed, as well as a survey of recent developments in this field.

Background

It is first necessary to understand for what purpose and under what constraints portable counter-proliferation technologies are developed. The IAEA is charged with inspection of global nuclear facilities to ensure that each signatory nation is in compliance with the NPT. However, as a subsidiary organization of the United Nations, the IAEA does not have direct enforcement capabilities in-house. The IAEA furnishes technical expertise and provides recommendations to policy makers (e.g. the UN Security Council) concerning whether a particular country's activities constitute a nuclear proliferation risk. This is significant because the IAEA is not authorized or empowered to use force to conduct its inspections and must rely upon the good faith of the nations it inspects. Most IAEA inspections are routine and announced (albeit often with less than 48 hours advance

CPT Grant V. Mallalieu is the Deputy Army Theater Counterintelligence Coordinating Authority on the Eighth U.S. Army staff in Camp Humphreys, Korea. He has a B.S. in nuclear engineering with a minor in grand strategy from the U.S. Military Academy at West Point. He was previously assigned as an infantry Platoon Leader at 1st Battalion, 4th Infantry Regiment in Germany. His email address is grant.v.mallalieu.mil@mail.mil.

notice), though many NPT signatory states also have agreements that authorize the IAEA to send in a mobile team to conduct unannounced inspections. Inspecting at irregular intervals ensures that the facility does not have time to alter or obscure large scale nuclear operations, though any advance notice may provide a facility's personnel a head-start in hiding a violation. Thus, to be effective, a counter-proliferation technology ought to detect even small amounts of nuclear material, which may also be hidden and/or shielded.

The political implications of an IAEA inspection can be immense. The IAEA maintains a public list of nations which are established as verified adherents to the NPT, a status which signals to the international community that a signatory nation is complying with the NPT in good faith. The removal of this status (even though the removal may officially denote ambiguity of compliance, and not that a country is weaponizing per se) can have enormous diplomatic implications, so the results of an inspection ought to be based upon the most sophisticated and reliable technologies available.

The technical requirements of portable counter-proliferation technologies represent a delicate balance, in which the IAEA must obtain enough information about a nuclear facility to confirm NPT compliance without going so far as to collect data which a country may rightfully regard as proprietary, sensitive, or classified. The gold standard is to conduct an inspection using methods which fall exclusively under the category of Non-Destructive Assay (NDA), sometimes also referred to as Non-Destructive Analysis, though more invasive methods may be necessary in some cases. NDA methods constitute any detection techniques which do not involve the physical destruction, alteration, or disassembly of the nuclear apparatuses under consideration. NDA techniques are more likely to be acceptable to the signatory state because they are far less expensive (because the state will not have to reassemble complex nuclear systems) and do not allow the inspectors to directly access classified devices or information. NDA methods have evolved tremendously over the decades in which IAEA has been conducting in situ inspections and now encompass an array of capabilities which include determination of source isotope and enrichment, determination of source geometry and location, and quantification of source mass. The current state of research of each of these will be explored below.

Current Detection Techniques

In broad terms, the field of portable counter-proliferation technologies has been transformed over the past few decades, not by advances in basic science, but through a host of software advancements which have allowed engineers to extract more information from the signature emitted by a radioactive source. Of all counter-proliferation technologies, source detection is the simplest, as it is fairly straightforward to detect when an area has significantly greater radioactive flux than that attributable to the expected background radiation. For that reason, this paper will not discuss source detection specifically, as it is an inherent part of all types of detectors.

Isotopic Composition and Enrichment

Determining the isotopic composition and enrichment of the source is far less straightforward. The rest of this discussion primarily pertains to gamma-emitting isotopes (e.g. uranium sources), as a thorough examination of portable neutron-emitting source detection (from a weapons grade plutonium source, for example) would require a separate article . For neutron-emitting sources, only Neutron Coincidence Counting (NCC) will be discussed, as it is among the most widely used and effective methods for identifying neutron-emitters.

One method for identifying the isotopic composition and enrichment of a suspected uranium source involves a system that incorporates Multi-Group Analysis for Uranium (MGAU). This technology, produced by Canberra, provides “sophisticated analysis using multiplet deconvolution [which] eliminates the need for efficiency calibration based on matrix density, matrix type, or container characteristics.”3 This is a useful feature for an inspection team on a strict timeline, as it limits the amount of time spent in calibrating traditional detectors based on sources of known activity. MGAU uses the relative ratios of gamma peaks (known as the peak ratio method) to determine the isotopic composition of a source based on its known gamma signature, and, by extension, its enrichment. Software conducts this pattern-matching nearly instantly.

Another method is NaIGEM , which augments a traditional sodium iodide detector with software that provides generally similar results to MGAU. The key difference between the two technologies is in the statistical methods by which they arrive at a determination of the isotopic identification and enrichment. NaIGEM uses the peak fitting method to make these determinations, which may return distorted results if the source is well-shielded. However, NaIGEM is more accurate than MGAU for relatively unshielded sources (as the gamma signatures are better preserved, one can look at the gammas absolute abundances, and not just their ratios).

WinU235 identifies the isotopic composition and enrichment of a suspected uranium source. WinU235 uses the enrichment meter method, which has proven remarkably accurate in determining the enrichment of large uranium sources. However, in order for the Win235 software to provide an accurate result, it assumes the uranium source to be “infinitely thick,” for all effective purposes. Uranium has a very high cross section with respect to the energetic gammas it emits, so an “infinitely thick” uranium source need be less than a millimeter thick to satisfy this requirement. A very thin source, however, would have a slightly different gamma signature, as the gamma rays will not have interacted with (i.e. scattered off of) the surrounding uranium nuclei in the expected manner.

A final means of isotopic identification, as mentioned above, is Neutron Coincidence Counting, a method which has been discussed since at least the 1960s,4 but which has made great strides in recent years. This method is distinct insomuch as it relies upon the fact that spontaneous fission neutrons and prompt neutrons are emitted virtually simultaneously from a neutron-emitting source (such as plutonium), so the counter can identify pairs of radiation incidents which are “coincident” to determine whether those particles derive from a neutron emitting source. The exact timing of these incidences can further clarify what isotope of neutron emitter is present.

Source Geometry

The In Situ Object Counting System (ISOCS) is a software tool that can adjust its output based on the expected geometry of a source hidden inside another object, such as a metal casing. ISOCS allows the inspector to input a “guess” of about 20 common geometries for a source and can use this information to provide a more accurate calibration of the gamma signature it receives. Notably, ISOCS does not rely upon an assumption of an infinitely thick uranium source (i.e. ISOCS does not make assumptions about the source's internal shielding), so it can provide an accurate result independent of the source's geometry. Also of note is the fact that this method generally takes quite a while to provide a measurement (usually at least 10 minutes, depending on source intensity) so it does have an important limitation, especially when operating within a facility that may require many measurements.

Mass Determination

Active Well Coincidence Counters (AWCC), along with other active interrogation methods, are the primary means of determining the masses of uranium isotopes present in a sample. They work by using a neutron emitting source (often americium-lithium) to filter through the suspected uranium source, with a detector on the opposite side of the suspected source registering the signature of the radiation after it passes through. The exact profile of the neutrons emitted from the Am-Li source can be compared (via software) against reference values to determine the quantity and isotopic composition of uranium through which the Am-Li's radiation passed.

Future Research and Conclusions

A host of new portable technologies have been developed to confront the proliferation threat, but greater research is needed. Almost as quickly as counter-proliferation technologies can be fielded, new methods of masking nuclear materials are being developed, and the sophistication of international smuggling and proliferation networks is a constant threat. Software innovations enable regulatory agencies to update their counter-proliferation techniques more quickly, often without having to replace expensive legacy hardware. Nuclear detection is not the only tool in the counter-proliferation fight (tracing financial supply chains is another method, for example), but the aforementioned counter-proliferation technologies play an important role in fulfilling the IAEA's mandate to promote "Atoms for Peace."

Notes

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Application of Path Planning Algorithms to Robot Navigation in Radiation Plumes and Fields

MAJ Omololu Makinde[1], Shelly Bagchi[2,3,] Christian H. Ramos[2,4,] Christopher Wheatley[2,5]

[1]Nuclear Disablement Team 2, 20th Chemical Biological Nuclear Radiological and Explosive Command

Aberdeen Proving Grounds, MD 21005

[2]University Of Maryland, College Park, MD 20742

MAJ Makinde is currently the Department Head of Radiation Sciences Department at the Armed Forces Radiobiology Research Institute of the Uniformed Services University of the Health Sciences in Bethesda MD. He has a B.S in Mechanical Engineering from the University Of South Carolina, a M.S. Mechanical and Nuclear Engineering from Virginia Commonwealth University. He was previously assigned as a member of The Nuclear Disablement Teams at The 20th CBRNE Command. His email address is omololu.makinde@usuhs.edu.

Shelly Bagchi is an Electrical Engineer at the National Institute of Standards and Technology in Gaithersburg, Maryland. She received her Master's in Electrical Engineering from the Georgia Institute of Technology in 2015, and her Bachelors in Computer Engineering from the George Washington University in 2013. Her research interests are in human-robot interaction, situational awareness, and augmented reality. She previously co-taught the introductory Artificial Intelligence class in Georgia Tech's Online Masters in Computer Science program, a program which has enrolled over 10,000 students. She participates in the ASTM Standards Committee E57 on 3D Imaging Systems and the IEEE Study Group on Metrology for Human-Robot Interaction. Shelly also serves as an organizer for the 'Test Methods and Metrics for HRI' Workshop, which occurs annually at the ACM/IEEE International Conference on Human-Robot Interaction, as well as the 'Artificial Intelligence for Human-Robot Interaction' Symposium, part of the annual AAAI Fall Symposium Series. Her email address is shelly.bagchi@nist.gov.

Christian H. Ramos is currently working as a researcher in the field of Robotics in Lakehurst, NJ. He has a B.E. in Electrical Engineering, M.S. in Electrical Engineering and M.S. in Computer Science from Stevens Institute of Technology. He is currently pursuing a Master's in Robotics Engineering at the University of Maryland. His email address is perseverancia@hotmail.com.

Christopher Wheatley is currently a Senior Associate Systems Engineer for L3Harris Technologies in Washington, DC. His work is mostly in support of programs related to Automatic Dependent Surveillance Broadcast (ADS-B), a primary FAA NextGen technology for real-time aircraft surveillance. Christopher earned a B.S. in Aerospace Engineering from the University of Maryland (College Park) in May of 2017, followed by earning a Master of Engineering in Systems Engineering from the University of Maryland (College Park) in December of 2020. His email address is Chris.Wheatley@L3Harris.com.

Introduction

The nuclear industry can be divided into four major fields of employment, namely, nuclear power, nuclear medicine, nuclear research and nuclear weapons. All components of these fields use facilities and fuel generated from the nuclear fuel cycle. Since the development of the first atomic weapon and execution of the Trinity Test, characterizing the radiation contamination field has been a scientific and operational challenge.

The reactor meltdown at Three Mile Island (TMI) was the first spur in robotic development in the nuclear field. At the time, the robotics industry was less than 20 years old, with little to no advances in computer vision, controls theory or planning, and with bulky hardware [1]. The accident led to an acceleration in research and development of robots for nuclear power plants. However, robots that could conduct autonomous or semi-autonomous tasks in dangerous environments were just being conceptualized.

The TMI accident led to the extensive use of four robots, namely SISI, Rosa, Rover and Fred, for remote surveillance, core defueling and decontamination [1]. We know that during nuclear incidents like TMI, Chernobyl, or Fukushima, there is an urgent need to characterize site conditions as soon as possible [2]. Research in robotics for the nuclear industry generally surround development of materials and building automated components that can survive the harsh radiation environment. Application of development in the field for surveying hazardous environments focuses on material and shielding solutions, software and algorithms can also play a vital role.

This paper looks at the 2019 review of ground-based robotic systems for the characterization of nuclear environments [3] and shows how the addition and refinement of search algorithms can improve the planning and execution processes for early characterization of the radiation field.

Related Work

Unlike most industries that use robots out of a desire to improve product quality or gain a competitive edge, the use of robots in the nuclear industry is imperative to reduce the hazards to humans associated with working in high radiation field.

Hence there is a large body of work related to development of robots equipped with arms and cameras to move objects. Like robotic platforms developed for TMI clean-up [4]. Unmanned Aerial Vehicles (UAVs) are also being developed for radiation detection. These UAVs can map an area without the risk of exposing humans to radiation.

In the aftermath of the Fukushima Daiichi reactor accident of 2011, shortfalls in robotics for nuclear power plant accidents became evident [3]. The international community learned that none of the technology developed at that time could withstand the accumulated doses radiating from a core breach without significant cooling time. Major development efforts are currently underway to develop robots and radiation-hardened electronics that would solve this problem [2].

Robot model	Birthday	Institute	Size (W×L×H /mm)	Weight (kg)	Dose	Communication
FRIGO-MA	2012	Mitsubishi	490×650×750	38	10 Gy/h	Wired/Wireless
Survey Runner	2012	Topy	510×505×830	45	1000 Gy	Wired
Surface boat	2013	Hitachi	330×900×293	27	--	Wired
SC-ROV	2013	IRID	280×305×140	10	0.5 Gy/h Total 200 Gy	Wired
Rosemary	2013	IRID	500(W)×700(H)	65	--	Wireless
Raccoon	2013	ATOX	403×632×302	35	10 Gy/h	Wired
Arounder	2013	IRID	740×1200×1700	550	10 Gy/h	Wired
Kanicrane	2014	Hitachi	700×2360×1430	1250	10 Gy/h	Wired
Gengo	2014	IRID	420×480×375	22	200 Gy	Wired
Trydiver	2014	IRID	480×628×378	40	200 Gy	Wired
Telesoopic	2014	IRID	509×440×826	70	1000 Gy	Wired/Wireless
Lake Fisher	2014	IRID	658×1038×1016	180	1000 Gy	Wired/Wireless
Sakura	2014	IRID	390(W)×500(H)	35	--	Wired/Wireless
MEISTeR	2014	IRID	700×1250×1300	550	100 Gy/h 1000 Gy	Wired
Smartphone	2015	TEPCO	77×319×105	0.787	1.3 Gy/h	Wireless
B1	2015	IRID	70×600×95	--	10 Gy/h 1000 Gy	Wired
Scorpion	2017	IRID	90×550×90	--	100 Gy/h Total 1000 Gy	Wired
PMORPH	2017	IRID	70×700×95	--	100 Gy/h Total 1000 Gy	Wired
DRV	2017	IRID	90×300×90	--	70 Gy/h	Wired
ROV	2017	IRID	130(D)×300	2	200 Gy	Wired

Table 1: Partial performance parameters of response robots for Fukushima Daiichi accident

Table 1 shows the failure doses for robots developed for the Fukushima Daiichi accident [2]. None of these robots are capable of conducting area radiation characterization at radiation levels that would have been seen immediately after the accident, however, integrating path planning into the robot programming can help find the fastest path to characterizing an area and returning the robot prior to receiving a catastrophic total dose.

Models

<u>Radiation Field Modelling</u>

The Defense Land Fallout Interpretive Code (DELFIC) Fallout Planning Tool model a 1.2kt nuclear detonation in College Park Maryland. Figure 1 shows the plume from the model.

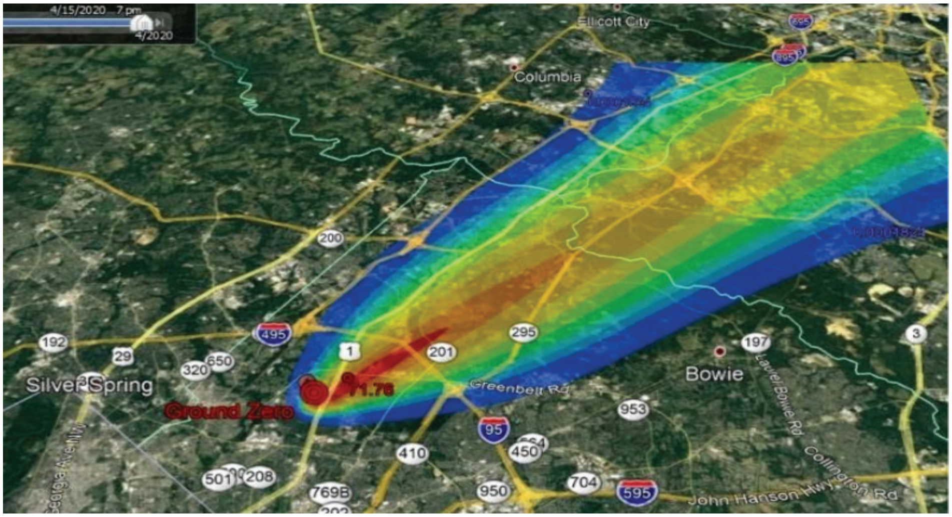

Figure 1. DELFIC plume for 1.2kt detonation at College Park, MD

However, due to release restrictions, further details of the model cannot be used for current analysis. Instead, a set of equations are used to model the exposure rate 24 hours after the incident. The detonation is modelled as a point isotropic source of cesium 137 radionuclide emitting 0.663 MeV gamma characteristic energy in dry air near sea level. Exposure as a function of distance, and obstacle are calculated with equations in Figure 2 and compared to values in Table 2.

Level (@R/h)	Cumulative Area (km^2)	Area (km^2)	Azimuth	Range (km)	Cell Count
30.0	0.2	0.2	154.2	0.3	97
10.0	0.7	0.5	106.5	0.6	198
3.0	2.4	1.7	104.8	1.0	680
1.0	6.8	4.4	95.3	1.8	1741
0.3	18.9	12.1	91.2	3.0	4826
0.1	48.1	29.2	90.8	4.6	11685
0.03	148.7	100.6	93.1	7.7	40251
0.01	442.1	293.4	94.5	12.8	117355
> 0	**	**	**	**	**

Table 2: Exposure rates from DEFLIC

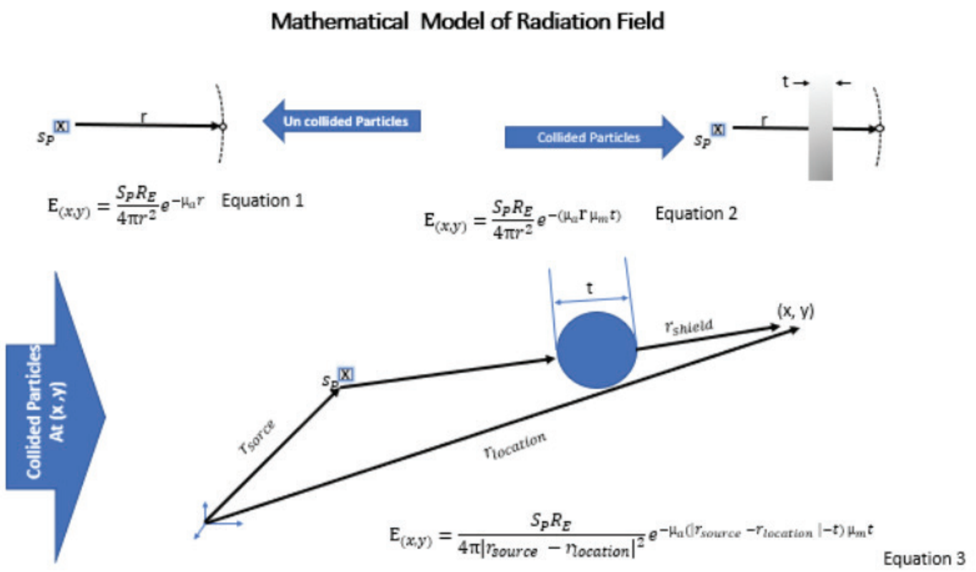

Figure 2: Exposure for Point isotropic source mathematical model

Sampling-Based Planning Algorithms

The methods implemented for this problem include two state-of-the-art sampling-based planning algorithms: Rapidly-Exploring Random Trees (RRT) and RRT*. RRT was developed in 2006 by LaValle as a motion planning algorithm which drives map exploration via movement towards randomly appearing nodes on the map. One notable feature of this method, which makes it useful for exploration within a radiation field, is the cost function. This cost function can be tailored based on heuristics that are specific to the problem of interest. For this topic, the primary metrics of concern are distance (from current node to random sample) as well as exposure rate on the map at the location of the current node. In this case, the distance already travelled (cost2come) is not of concern and thus is not incorporated into the RRT cost function. The driver for these modifications is due to the goal of obtaining a feasible path plan from start to goal, where shortest-distance is the primary factor until the robot enters a region of high radiation exposure, at which point shortest-distance becomes irrelevant and lowest-exposure paths become much more heavily favored.

```
SIMPLE_RDT(q_0)
  G.init(q_0);
  for i = 1 to k do
      G.add_vertex(α(i));
      q_n ← NEAREST(S(G), α(i));
      G.add_edge(q_n, α(i));
```

$$S = \bigcup_{e \in E} e([0,1]).$$

$$\mathcal{G}(V, E)$$

Figure 5.16: The basic algorithm for constructing RDTs (which includes RRTs as a special case) when there are no obstacles. It requires the availability of a dense sequence, α, and iteratively connects from $\alpha(i)$ to the nearest point among all those reached by $\mathcal{G}$.

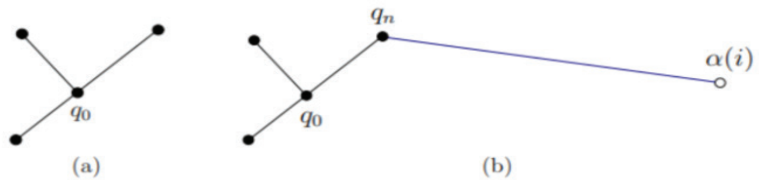

Figure 5.17: (a) Suppose inductively that this tree has been constructed so far using the algorithm in Figure 5.16. (b) A new edge is added that connects from the sample $\alpha(i)$ to the nearest point in S, which is the vertex q_n.

Figure 3: Sample of RRT Algorithm Search Space.

Figure 3 shows a sample implementation of RRT. Note that RRT does not necessarily provide the optimal or ‘best’ solution. In this case, an “optimal” path is not the desired goal, in terms of shortest distance. The goal for RRT, as it applies to exploration of radioactive outdoor environments, is to obtain a feasible path plan which factors in both shortest-distance as well as exposure. Factoring in exposure, especially in notably high radioactive locations on the map, will cause exploration to venture in a way that is not always of shortest distance, but rather in such a way that attempts to circumvent/avoid regions of high exposure until a sufficiently high number of random samples forces the expanding RRT graph to continue exploring until the goal is reached.

RRT* was later developed by Karaman and Frazzoli as a variant of RRT which returns a probably optimal path (assuming one is available) [6]. The RRT* pseudocode can be seen in Figure 4. This paper applies advantages of RRT and RRT* to two separate scenarios.

```
Algorithm 4: Extend_RRT*
V' ← V; E' ← E;
x_nearest ← Nearest(G, x);
x_new ← Steer(x_nearest, x);
if ObstacleFree(x_nearest, x_new) then
    V' ← V' ∪ {x_new};
    x_min ← x_nearest;
    X_near ← Near(G, x_new, |V|);
    for all x_near ∈ X_near do
        if ObstacleFree(x_near, x_new) then
            c' ← Cost(x_near) + c(Line(x_near, x_new));
            if c' < Cost(x_new) then
                x_min ← x_near;
    E' ← E' ∪ {(x_min, x_new)};
    for all x_near ∈ X_near \ {x_min} do
        if ObstacleFree(x_new, x_near) and
        Cost(x_near) >
        Cost(x_new) + c(Line(x_new, x_near)) then
            x_parent ← Parent(x_near);
            E' ← E' \ {(x_parent, x_near)};
            E' ← E' ∪ {(x_new, x_near)};
return G' = (V', E')
```

Figure 4: RRT* pseudocode [7].

Methods

Scenario 1: Autonomous Search and Planning in an Outdoor Radiation Field

The goal of Scenario 1 is to demonstrate the use of a sampling-based search algorithm to provide a path with the least total accumulated exposure. The scenario is modelled to represent residual gamma radiation 24 hours after a 1.2 kt nuclear weapon detonation. It involves radiation fields in a wide outdoor area, surrounded by a field of debris. Within this environment is a radiation source that needs to be identified, characterized, and/or recovered.

The source used for mathematical calculation in this scenario is a Cesium-137 radionuclide emitting 9.5 x 10^{17} particles as an isotropic radiating point source in air. Particles move radially outward until interactions with debris which are shown as buildings and vehicles in Figure 5. The exposure at any point p is then calculated by:

$$Exposure\ Rate\ \left(\frac{R}{hr}\right) = \frac{S_P \mathcal{R}_X(E)}{4\pi|r_s - r_t|^2} e^{-\sum(\mu_i t_i)}$$

Where:

SP = number of particles emitted at the source per unit time,

$\mathcal{R}_X(E) = 1.835 \times 10^{-8} E \left(\frac{\mu_{en}(E)}{\rho}\right)_{air}$ is the photon exposure response function for energy E = 0.662 MeV,

Scenario 1 considers radioactive exposure as the primary driver for map exploration. Exposure is calculated at every point within the 450m x 232m map space (using 1-m grid resolution). This scenario assumes two obstacle types, buildings and vehicles. Buildings are assumed to be composed entirely of concrete and vehicles are assumed to be made of steel and chromium. The chromium components of the vehicles are modelled as an irradiation of chromium 50 to produce characteristic chromium 51 with 0.323 MeV gamma ray from neutron activation. Figure 5 shows a top-down view of the Scenario 1 map, a southern section of the University of Maryland (College Park) with pink polygons representing buildings (concrete obstacles) and green polygons representing vehicles (chromium-steel sources).

Figure 5: Google Earth aerial view of search area

In this scenario, the RICA robot in Figure 6 will be used to search the area in a simulated environment. RICA is a robot developed for radiation fields, and incorporates a sturdy metal body, tank-tread based differential drive for outdoor navigation, and gamma cameras (Ioannis Tsitsimpelis 2019). For this simulation it was assumed that the RICA robot could explore any terrain besides buildings and parking lots.

Figure 6: RICA Robot [3]

The robot will incorporate exposure rate with location data to search through the field using rapidly-exploring random trees (RRT). The RRT algorithm will find a path from a start point to a goal point by a constant evaluation of the nearest unexplored node. In this context, 'nearest node' indicates the existing node of lowest total cost. Each node k on the map is evaluated using the following total cost function:

$$\text{Total Cost}_k = w_1 * (\text{Cost2Go}_k) + w_2 * (\text{Exposure Rate}_k) \qquad \text{(Eq 2)}$$

Where:
Cost2Go=Euclidean distance from current node to random sample (m)
Exposure Rate (Eq 1) = Sum of the total radiation exposure rate at current node location (Roentgen/hr), influenced by the main source as well as surrounding obstacles
w1, w2 = Weights established via trial and error during algorithm implementation.

Figure 7 shows exposure rate in air represented as a homogeneous medium from the Cesium-137 point source. The source is located at the top right corner of the map, with the colour gradient from yellow to blue representing the isotropic radiation from the source.

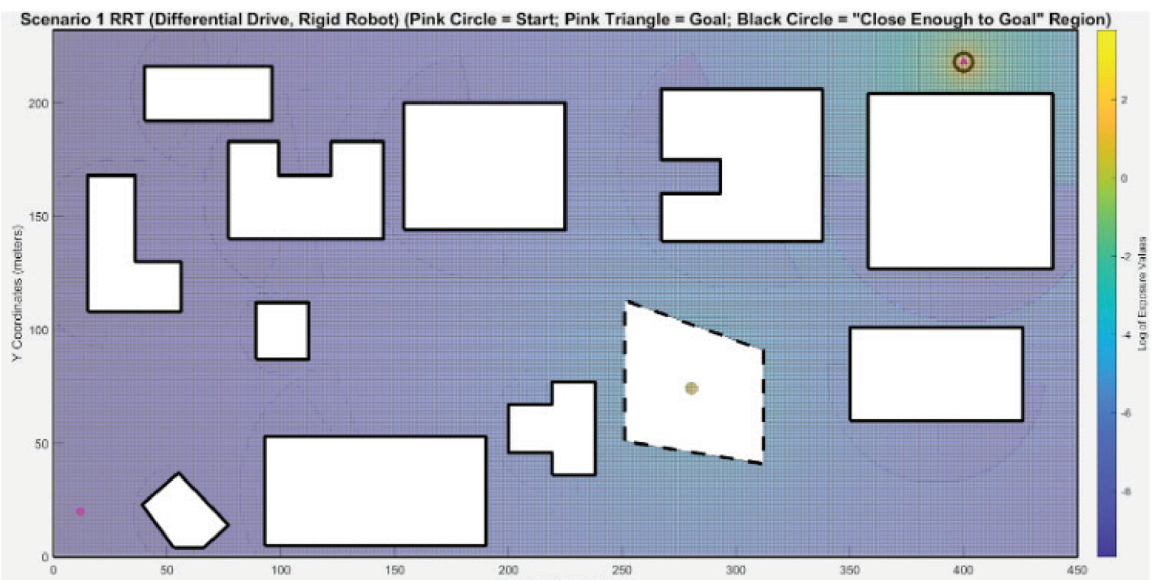

Figure 7: MATLAB model of search area with point source in homogeneous medium (air)

To simulate the operations of the RICA robot in this radiation field, the map space will be defined in MATLAB to provide exposure rates at each point on the map. The pre-computed rates will be supplied into the RRT algorithm as part of the cost in each node. An abstracted breakdown of the RRT search algorithm is outlined in the flowchart in Figure 8.

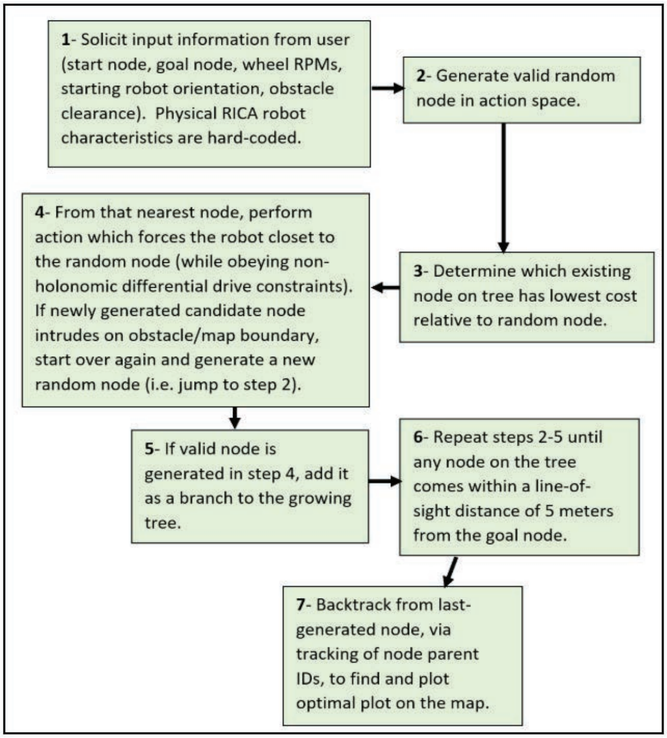

Figure 8: Rapidly-exploring random trees (RRT) algorithm flow chart.

Scenario 2: Optimal Path in Westinghouse Commercial Hot Cell

All nuclear processes that happen beyond a reactor require a hot cell. Hot cells are heavily shielded rooms with tele operators positioned outside, around a special layer of lead-shielded glass. Workers bring articles into the cell via shielded ports, cranes, and manipulators. Vision in hot cells is often limited due to degradation in the glass panes over years of operation. Also, damage to the facility due to equipment malfunctions or natural disasters can render the teleoperation unusable. Recovery and hot cell clean-up is an extremely hazardous endeavor that consists of either manipulating large shielded partitions to get to the source in the room, or waiting years for acceptable radiation levels in the room.

Since there is prior knowledge of the environment in a hot cell, one can send a small robot into the room with a camera in the case of loss of viewing capabilities in the windows. However, beyond a very short period, most cameras cannot withstand the high gamma radiation from spent fuel that is usually being processed in a hot cell; thus, the robot may not be functional by the time it reaches its goal, and also may not be retrievable. In this case, we intend to use Turtlebot 2 due to the small form factor and low cost to determine how far a robot can go inside the cell given an optimal path from a start to a goal point. This paper will use the RTT* algorithm to find the shortest navigable path to the source. The total exposure for this path is then calculated at each point to determine where the equipment failure will occur. Another application of the optimal path through the cell would be to determine the risk of criticality if a moderating element like a human moves along the path. This is useful because in situations where the radiation source is fissile or fissionable. Introduction of a moderated neutron could cause the environment to change from subcritical to critical thereby starting a chain reaction. Criticality calculation is an extremely specific and nuanced field of nuclear engineering that involves solving the diffusion transport equation for specific geometries. The key factors in any critical system is the geometry of all bodies, composition of fission radionuclide, and moderator. In a situation where a room composed of fissile material is currently not critical, a change into the environment by adding human beings would change the nuclear moderation and could lead to a critical configuration. Knowing the optimal path through such an area can allow for criticality calculations at each point on the path to determine the chance of criticality along that path. The hot cell under consideration is a Westinghouse commercial hot cell, shown in Figure 9.

Figure 9: Outside a Westinghouse Commercial plant high-level cell.

The hot cell is modelled in Python in an open configuration with three sources located next to respective shipping casks. Casks are modelled as lead shields. The cell is rated at 7000 R/hr, therefore the combined exposure rates from the sources is limited to this maximum. The equations in Figure 2 are used to calculate exposure rate at each point from all three sources, combined with shielding from each storage cask. Figure 10 shows the simulated room configuration plotted over a heat map of the sources' exposure rates in a homogeneous medium of argon. The lead-shielded casks are shown in white and a workbench is in purple.

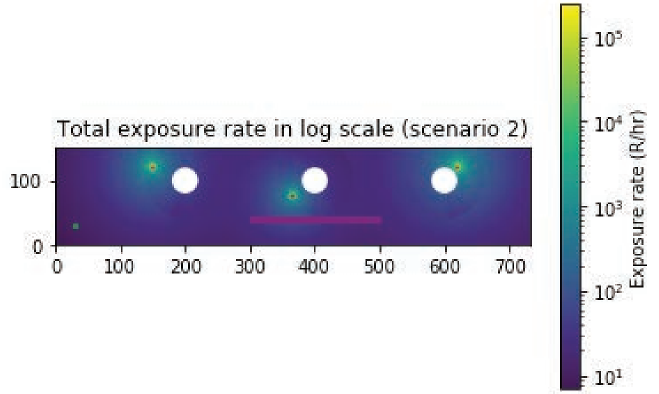

Figure 10: Hot cell objects shown over exposure rate heat map in Python.

The RRT* sampling method is used to search the cell. It utilizes a tree-based approach, which is summarized in the flow charts in Figure 11.

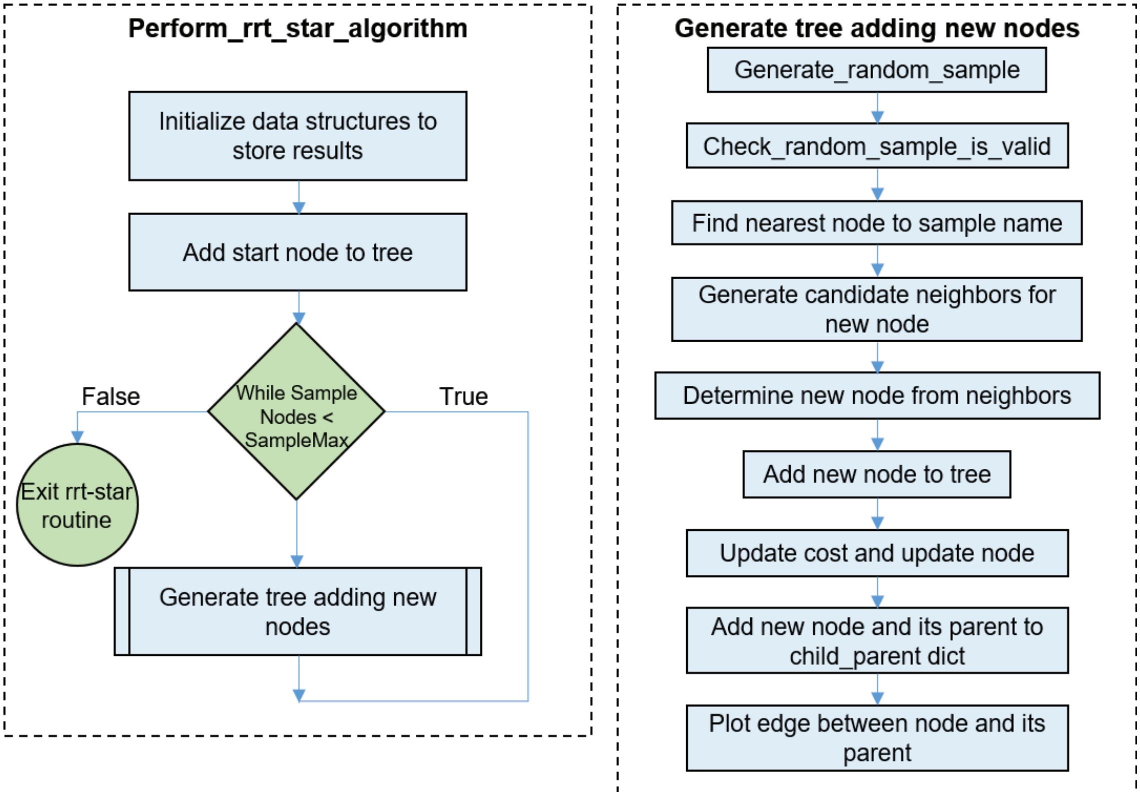

Figure 11: RRT* flow charts.

Robot and Environment Simulation

<u>Scenario 1: MATLAB and CoppeliaSim</u>

Scenario 1 implements the RRT algorithm, written in Matlab, and tested with a proof-of-concept 3D simulation in CoppeliaSim (previously known as V-REP, the Virtual Robot Experimentation Platform). For the simulation, buildings in the area are modelled as absorbing concrete polygons and shown in solid white. Cars are modelled as activated chromium polygons and shown in a grouping (e.g. parking lot area) with dashed borders. Hence, cars will add smaller, localized sources.

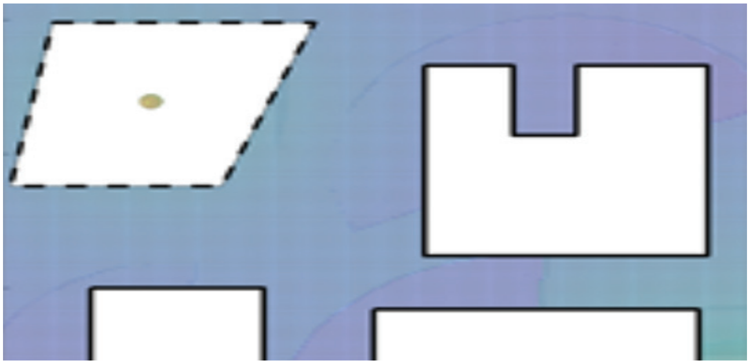

Figure 12: Concrete Obstacle Attenuations

Figure 12 shows a close-up, top-down view of some of the concrete obstacles attenuating the radiation exposure. The attenuations are estimated as hemispheres in the opposite direction of the source to model how the buildings will provide some shielding, i.e. lower-exposure regions. Additionally, a lighter region can be seen around the diamond-shaped parking lot obstacle, which absorbs and re-emits a low amount of radiation, as opposed to the attenuating concrete. Vehicles within the parking lot are assumed to be composed of chromium metal.

The cost function from Eq. 2 is used for RRT sampling of the area. The weights were determined by trial and error after examining the simulated exposure values. The implemented weight for radiation exposure consideration (w2) is 0.000001 and the implemented weight for distance consideration (w1) is 0.999999. The result of this configuration leads to the RRT algorithm heavily favouring shortest-distance exploration in areas of low radiation exposure, relative to the source strength, and heavily favouring lowest-exposure exploration in areas of high exposure. This is the ideal approach since the RICA robot is not notably sensitive to radiation exposure across the map, except for areas nearby the goal source.

Scenario 1 is modeled assuming differential drive constraints, meaning each wheel can drive with individual RPMs. For example, if the user inputs RPMs of [5,10] at the start of the simulation, then the following wheel speed configurations are available for performing RRT (for [Left Wheel RPM, Right Wheel RPM]): [0,0], [0,5], [5,0], [5,5], [5,10], [10,10], [0,10], [10,5].

From experimentation, it was determined that RRT exploration becomes infeasible if RPMs greater than 8 RPM are used. This is because, given the small dimensions and wheel separation of the RICA robot, the robot will tend to move in circular loops if sufficiently high RPMs are being implemented. Maximum wheel RPMs of 8 are assumed for the remainder of this analysis, as it allows for freedom to explore the map, but also yields a feasible/realistic path plan without recursive looping. Figure 13 compares how the exploration tree expands with different RPM assumptions. Note that RPMs even as high as 12 result in recursive looping, and RPMs of no greater than 8 allow for the freedom to perform useful/feasible actions without moving backwards.

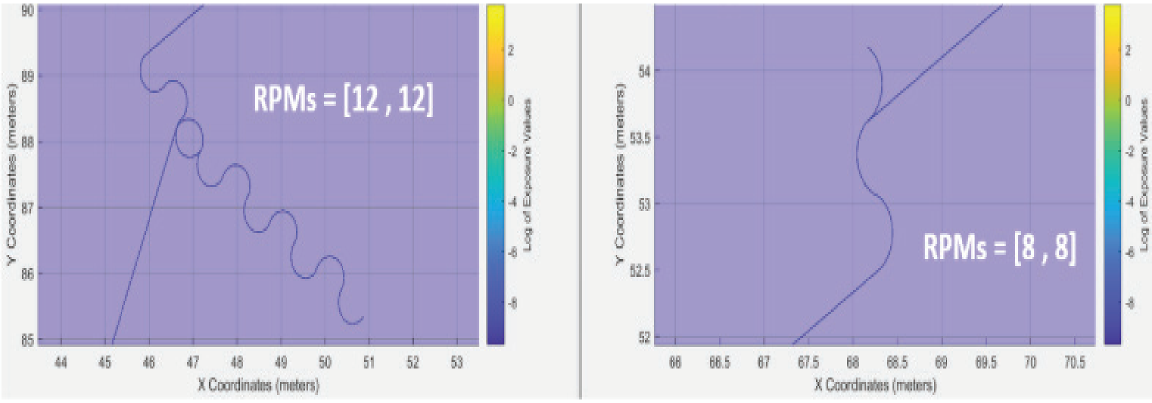

Figure 13: Tree Expansion Result for Different RPMs

Scenario 2: Python and ROS-Gazebo

Scenario 2 implements the hot cell map in Python 3.7, with a 3D simulation in ROS-Gazebo. The 2D simulated environment is shown in Figure 10, with the heat map of exposure visualized in log-scale, with shielding from lead casks and workbench in the room.

The RRT* algorithm was utilized for this scenario as previously mentioned. The cost function used was the sum, cost = cost2come + cost2go. This provides the room operators the fastest path from one point in the hot cell to any other point. This simulates a situation where the actual exposures are known by the planner, and the exposure limit for a camera or another tool is known. By summing exposures along the optimal path the planner knows when and where the camera or tool will most likely malfunction.

Another instance where the optimal path could be applied in hot cells, is the prediction of criticality. If the source in the cell was a fissile material like some isotopes of Uranium and Plutonium, the optimal path generated by RRT* then represents the path to move material through the space with the least amount of change to the environment configuration. Using codes that solve the diffusion transport equation, planners can check each position to determine “k effective” (measure of criticality of a system) when an object is in that position.

The number of samples, a user-determined parameter for RRT*, allows tuning of the algorithm for a tradeoff between runtime and accuracy / optimality [9]. From experimentation, 700 samples were used to provide a sufficiently direct path.

The Turtlebot 2 was represented in the non-holonomic environment by utilizing Dubins Curves [10]. The Dubin Car approach consists of modeling the robot as a car that can only move forward within non-holonomic constraints [11]. Therefore, Dubin Curves make use of a maximum turning rate to determine the minimum turning radius the robot travels as a path is generated from one node to the next. Dubin Curves are based on geometric analyses and use three basic moves, Left (L), Right(R) and Straight(S), to generate the following six combinations of movements: (LSL , RSR, RSL, LSR, RLR, and LRL). These motions are considered when implementing the RRT* algorithm for this scenario1 [12].

Figure 14 shows the representation of the world built in ROS-Gazebo. The Turtlebot 2 can be seen in the center of the scene.

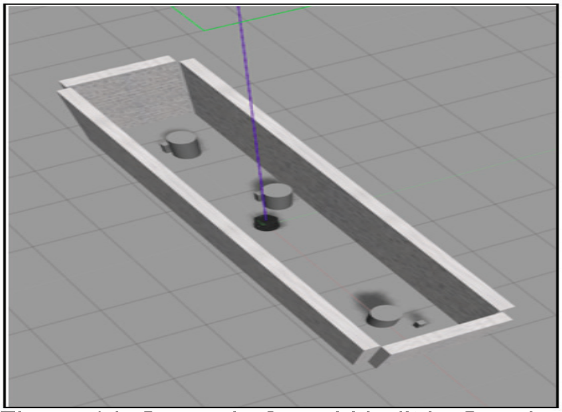

Figure 14: Scenario 2 world built in Gazebo.

Results

Scenario 1 Results

A sample RRT result can be seen in Figure 16, along with the exploration graph/tree. Note that, per the weights assigned within the cost function, that the path tends to prefer exploration within the attenuation regions created by the concrete obstacles (i.e. the hemispherical regions adjacent to each building obstacle). However, exploration becomes much more evasive as the exploration graph approaches the radiation source. This is by design such that the robot becomes much more careful while exploring around the source, and considers areas of low exposure rather than exploring the shortest distance in the direction of random samples.

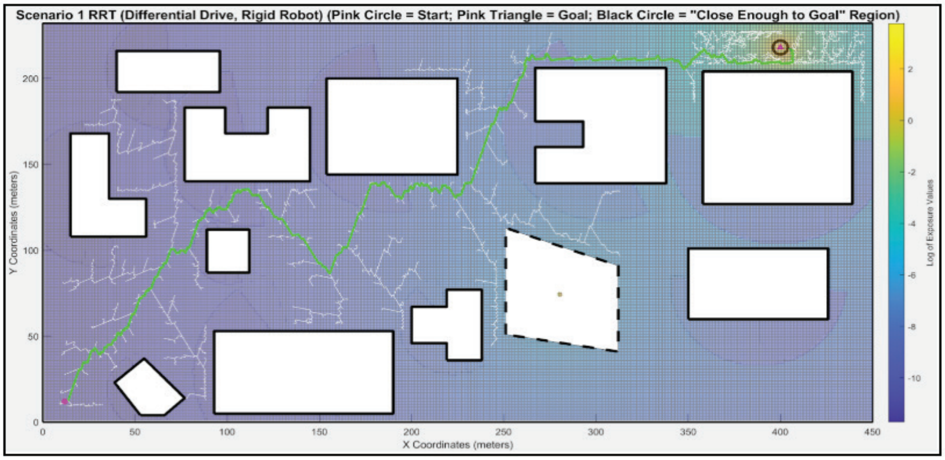

Figure 16: Scenario 1 RRT Exploration and Final Path Example

The final path is then projected onto the real-world map similar to Figures 5 and 18. RRT is nondeterministic, therefore it does not guarantee the same path over multiple runs. Multiple runs are needed to find the lowest-exposure path option.

Figure 17 below shows a trace of the same RRT motion planning example except in a VREP simulation environment. All obstacles were derived and constructed from primitive 3D shapes such as cuboids. A 3D model of the RICA robot was not readily available at the time of this analysis, so a Pioneer P3DX robot was used instead due to its similar dimensionality to the RICA robot.

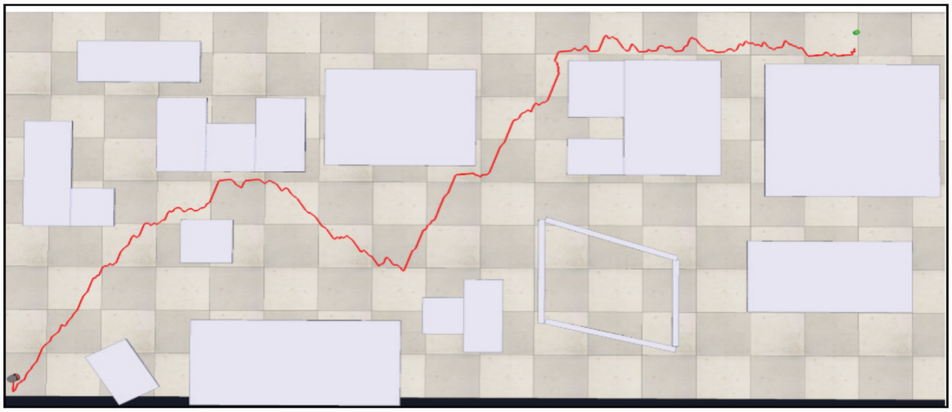

Figure 17: Scenario 1 RRT Exploration and Final Path Example.

Since RRT is a non-deterministic motion planning method, a post-analysis of multiple resulting paths is needed when devising a feasible plan. Figure 18 illustrates the best path for five separate simulation iterations where the robot starts in the bottom-right corner of the map, and where the goal source is in the top-left corner of the map. The differential drive parameters do not exceed 8 RPM for any of these simulations.

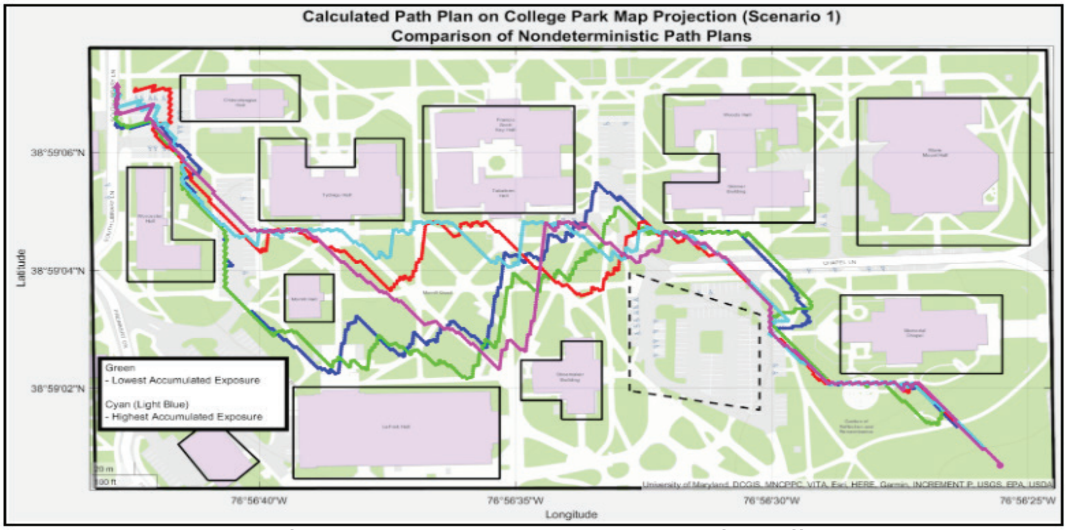

Figure 18: Visualization of 5 Non-Deterministic Path Plans for Differential Drive RRT (on Latitude/Longitude MATLAB Projection).

The most feasible plan in this case would be the green path, since it possesses the lowest accumulated radiation exposure throughout its transit. Visually this makes sense given the green path maintains the greatest clearance from the parking lot obstacle and given that it approaches the source from the south, shielding itself behind obstacles until arriving at the source. The cyan line possesses the highest accumulated radiation exposure, which makes sense given that it approaches the source in a 'zig-zag' motion. This behavior illustrates how the algorithm attempted to circumvent exploration near the source, but actually resulted in the robot exploring the highest-exposure area for a longer duration of time. Table 3 shows the list of accumulated exposure rates (in R/hr) for each of the five non-deterministic path plans that were assessed for differential-drive RRT.

Path Option	Total Accumulated Exposure (R/hr)
Green	3.4330e9
Blue	3.4788e9
Cyan	6.8317e9
Red	5.1594e9
Magenta	5.3008e9

Table 3: Exposure rate results from 5 runs of RRT

In a real-world implementation, a feasible path plan would be determined by evaluating many, many more path planning results. From these plans, the mean and standard deviation of total exposure rate can be calculated in the covariance matrix. This analysis would be useful in approximating the lower and upper limits on exposure in the situation, and determining whether the robot or human can be safely sent in.

Scenario 2 Results

A performance comparison was done for RRT vs RRT* to justify use of the heavier algorithm. Table 4 shows the total distance of paths achieved from each algorithm (with only one run of RRT), while Table 5 shows the runtime of the same test runs.

TEST POINTS	RRT	RRT*
Point Test 1 (110,110)	434.2 cm	120 cm
Point Test 2 (325,125)	1076 cm	454.1 cm
Point Test 3 (650,75)	1664 cm	1043.7 cm

Table 4: Total path distance from RRT VS RRT*

TEST POINTS	RRT	RRT* (700 samples)
Point Test 1 (110,110)	4 sec	142.3 min
Point Test 2 (325,125)	145 sec	143.3 min
Point Test 3 (650,75)	160 sec	121.3 min

Table 5: Algorithm runtime for RRT VS RRT*

As expected, RRT* yields a much shorter-distance path, but takes significantly longer to compute. This is acceptable in the hot cell scenario since the map is available ahead of time and the use is for post computational analysis of effects of the environment on equipment using the path, or the effect of moderators on the path.

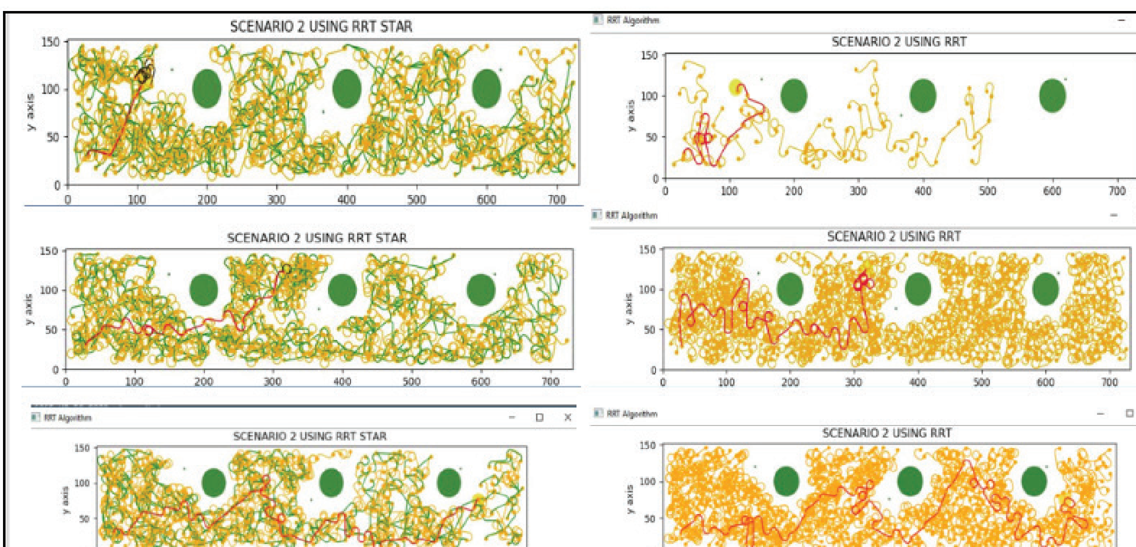

Figure 19: Visualization of RRT and RRT* exploration in the hot cell

Figure 19 shows the resulting exploration from the comparative tests, with RRT* on the left and RRT on the right. The RRT* paths can be seen to be more direct and contain less loops. However, both results would need to be smoothed and optimized for practical usage.

Conclusions & Future Work

The outcomes from Scenario 1 show that path planning can provide several useful outcomes in the case of a radiation detonation event. As demonstrated, a robot could be tasked to find the radiation source and create a rudimentary map of the exposure in the area. The robot could additionally be tasked to find a specific location in the area, potentially for search-and-rescue or retrieval of important or dangerous items. Finally, the resulting path can be useful for humans to enter the radiation area while limiting their exposure to a safe level if possible.

Scenario 2 provides a solution for radiation finding an optimal path through an indoor radiation field by using the path generated to determine the effects of exposure on items traveling through the path It also provides the criticality engineer a tool to use to determine effects of items moving through a subcritical nuclear system. The extreme exposure in this situation and difficulty of teleoperation makes autonomous navigation a necessity. Although the levels of exposure may result in failure of the robotic system, a partial plan can be achieved and picked up later on by a second mobile platform. Some hot cells, including the Westinghouse cell discussed above, also include equipment such as industrial robot arms. These could potentially be used to swap parts on the robot model as they fail.

As future work, Scenario 1 can be improved through implementation of a path-correction or optimization algorithm (such as RRT* or RRT SMART). The fidelity of the Scenario 1 model can be improved as well, namely in regards to defining the radiation/exposure field across the map. Currently, attenuation regions exist as semicircles, located 180 degrees opposite the direction of goal/source. These regions represent areas of the map that are shielded from source radiation. In reality, these regions exist more so as conic sections that trail off as they move farther away from the source. In the future, the fidelity of this model can be improved by implementing these more accurate geometries. Another improvement to the model would be to utilize the DELFIC tool for more accurate exposure readings.

In future work, Scenario 2 would be modified to consider the particle transport equations using Monte Carlo. This would implement the more accurate stochastic versions of the exposure formulas, rather than the deterministic approximations used for simplicity in these simulations. Further, criticality predictions could be incorporated into the planning algorithm. This would allow us to determine whether a human can potentially move through the cell without causing a nuclear chain reaction. Finally, simulating the swap of robots and/or parts in the hot cell can provide a more accurate representation of the whole scenario.

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The Priscilla Shot seen here was a part of the Plumbbob Series of nuclear tests conducted by the United States.
This shot, conducted 24 June 1957, contributed to the study of nuclear effects on military equipment, materiel, structures, and ordnance. (Photo provided by Los Alamos National Laboratory Historical Department.)

Application of Domain-Aware Artificial Intelligence with Combat Power on the Nuclear Battlefield

MAJ Adam Seybert and Dr. Robert Prins
U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency (USANCA)

Combat Power on the Modern Battlefield

At its most basic distillation, success in battle stems from amassing power and leveraging it into an advantage against your enemy. As COL Huba Wass de Czege asserted, combat power influences the outcomes of battles when commanders bring their strength and resources against the enemy at the decisive place and time.[i] As such, combat power is not a static quantity, rather a measure relative to an enemy. Combat power relies upon a commander's use of leadership and information to leverage a unit's collective capabilities: movement and maneuver, intelligence, fires, sustainment, command and control, and protection.[ii] Collectively referred to as warfighting functions, these capabilities represent a unit's potential. Skilled leaders must possess the ability to turn this "combat potential" into effective "combat power."

Assessing combat power is more than just comparing relative quantitative force ratios (e.g. force ratios 3:1 for offensive operations, 6:1 for defensive operations).[iii] Commanders and their staffs must use all available information to analyze both qualitative and quantitative factors in the operations environment and find opportunities to exploit enemy weakness. As ADP 5-0 highlights, success depends on the efficiency with which commanders can understand, visualize, and describe their environment. By being able to collect, organize, and process information quickly and accurately, they are better prepared to direct, lead, and assess their forces.[iv] As Boyd explains, "The ability to operate at a faster tempo or rhythm than an adversary enables one to fold the adversary back inside himself so that he can neither appreciate nor keep up with what is going on."[v]

However, the modern battlefield is a particularly challenging environment to assess. Containing a diverse collection of combat systems, both crew-served and autonomous, commanders rely on a massive flow of information needed for real-time operational characterization. Artificial Intelligence (AI) systems can afford military planners distilled, reliable, and

Major Adam Seybert is a Nuclear Effects Analyst within the Survivability and Effects Analysis Division at USANCA. He has a B.S. in Mathematics from the United States Military Academy and an M.S. in Nuclear Engineering from the University of Tennessee. He was previously assigned a program manager at the Defense Threat Reduction Agency. His email address is adam.g.seybert.mil@mail.mil

Dr. Rob Prins is the Survivability and Effects Analysis Division Chief within USANCA. He has a Ph.D. in Medical Health Physics from Columbia University, an M.S. in Medical Physics from Vanderbilt University, and a B.S. in Engineering Physics from the United States Military Academy. His email address is robert.d.prins.civ@mail.mil.

specifically applicable information, thereby increasing the speed of decision and action. Whether it is filtering relevant data based on the commander's critical information requirements or highlighting anomalies, AI can help clarify opportunities to address battlefield threats. AI is a force multiplier. It assists modern leaders to integrate a host of data concurrently collected across the battlefield and to develop situational awareness with which the commander can then apply their rigorous decision logic.

Conflicts with near-peer adversaries will arguably force leaders to operate in both conventional and nuclear environments… sometimes simultaneously. Fighting in and through conventional-nuclear battlefields presents compounding challenges and adds complexities in the decision-making process. The destructive capabilities of non-strategic nuclear weapons present the potential for destruction at both local and regional scale. Additionally, nuclear weapon effects pose both short and long-term problems that a commander must face to achieve success. Second order effects, such as non-tangible psychological impacts on unit cohesion add to already degraded materiel and personnel performance. In short, the nuclear battlefield includes disparate and diverse technical data requiring commanders to make decisions with considerations for both short and long timescales.

While mitigating the physical and psychological effects of the conventional-nuclear battlefield with trained and properly equipped troops, the information demand required to fight in these environments will be a challenge for even the most well prepared units. Specialized CBRN personnel help with the analysis, but with limited personnel per unit, it is easy to see situations in which these personnel cannot keep pace with the analytical demands required. AI applications present an opportunity to fill these gaps; however, any application must be robust, reliable, and accurate. These applications, when rigorously developed, provide information to the commander with "justified confidence."[vi] A specific field of AI, domain-aware AI, offers the benefits of interpretability and defensibility, while still adding efficiency to the staff and commander's decision-making process.

Domain Aware Artificial Intelligence

As highlighted by Angela Sheffield in the previous CWMD Journal issue (Fall 2020), National Nuclear Security Administration's (NNSA) Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) continues to make significant progress in building AI systems to detect very early indicators of foreign activities to develop nuclear weapons-usable capabilities.[vii] Early indicators provide critical contextual information across the myriad of Chemical, Biological, Radiological, and Nuclear (CBRN) precursor activities.

The major challenge with the use of commercial-off-the-shelf (COTS) AI tools for defense applications is suitability in situations with limited data or tools that ignore the laws of physics in making predictions. These "black-box" methods may do well at prediction, but without an understanding of "why" the system made the prediction, results may not be actionable. The DNN R&D work focuses on applying non-proliferation domain-knowledge to overcome the limitations of traditional AI. In addition to expert knowledge, domain-aware AI also uses synthetic data generation and physics-based logic for model development. These domain-aware methods produce traceable predictions and actionable decisions.

In many ways, the pursuit of early proliferation detection mirrors the hunt for rapid post-detonation characterization methods for DOD direct-support, force employment, and Defense Support to Civil Authorities (DSCA). While early proliferation detection results in a reduced threat of strategic surprise, early fallout characterization reduces risk to first responders during consequence management operations and allows greater operational freedom of movement for forces on a potential CBRN battlefield. However, sorting through useful information continues to challenge even the most knowledgeable person when presented with the sheer volume of available heterogeneous data, sources, and formats. Applying the same domain-aware and traceable AI technologies used for early detection of nuclear weapons development to post detonation nuclear modeling will bridge the gap in data discrimination. These methods also provide refined analysis, enabling more informed and rapid operations in a contaminated battlespace. Domain-aware application reduces decision support timelines for critical consequence management and contamination avoidance missions.

Domestic CBRN operations require in-depth modeling and environmental measurements to establish situational awareness and support Incident Command (IC) decision-making (Figure 1). A similar paradigm exists on the nuclear battlefield. Commanders and staffs must quickly quantify and characterize CBRN effects, understand the associated contextual implications, and make decisions to mitigate follow-on threats while operating at the speed of war. The technologies for measuring and modeling CBRN effects continue to grow more sophisticated, thereby reducing tactical risks in the early response timeline.[viii] However, the decision-making process for response and recovery remains cumbersome with the massive influx of available data from sensors, models, and ground reports. Advances in domain-aware AI will greatly enhance command decision making.

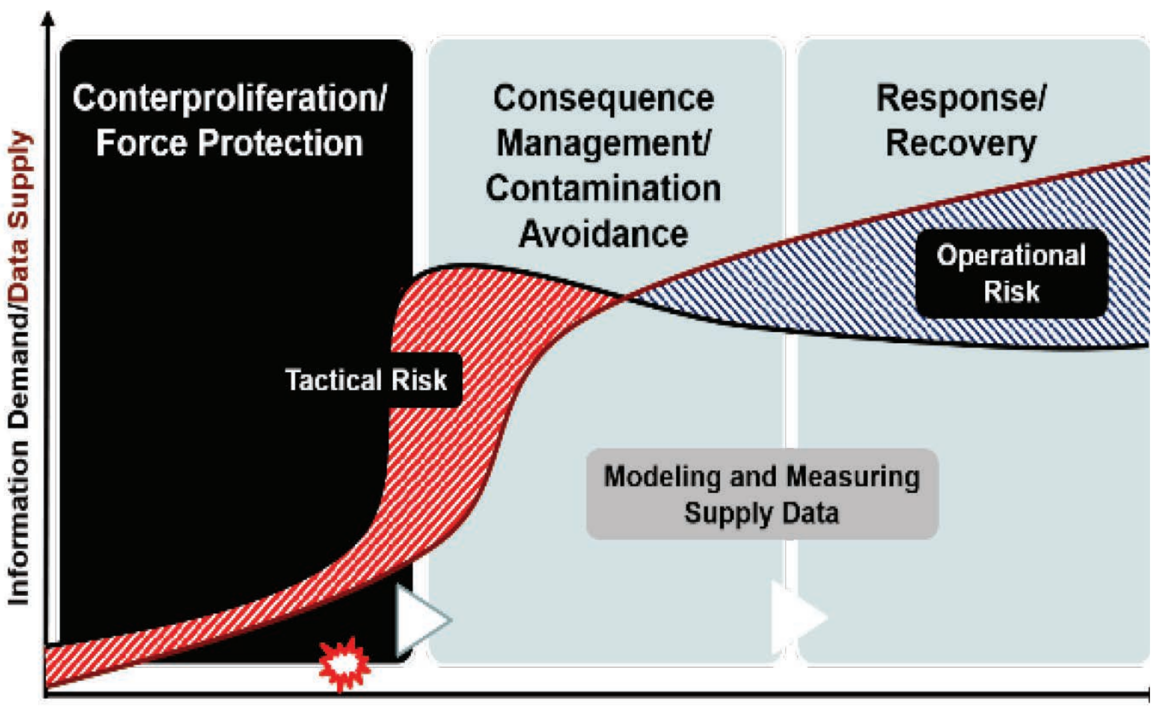

Figure 1. Lack of accurate sensor data presents tactical risk for early CBRN assessment. Later in the response, data flow can exceed IC processing capabilities—hindering response and recovery decision-making. (Figure generated by author)

Current State of the Art

The developmental scope for a whole-of-government CBRN disaster response solution is beyond the capabilities of any single government agency, but previous resource investments developed appropriate pieces of the response solution. Research and development efforts funded through NNSA's Office of Nuclear Incident Response developed high fidelity resources for response planning.[ix] Figure 2 shows an example of the Improvised Nuclear Device City Planning Resource (iCPR). Similarly, the Department of Homeland Security invested heavily in decision support tools for disaster response planning.[x] These resources are essential for response planning; however, capabilities for real-time response management are still limited.

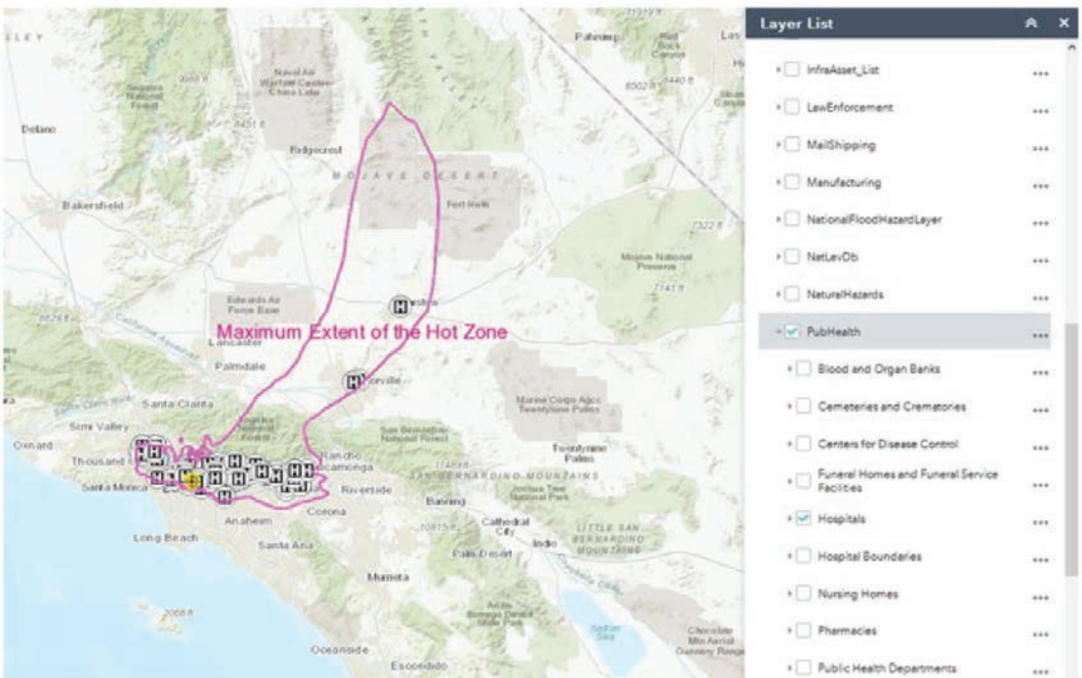

Figure 2. Screenshot of the Improvised Nuclear Device City Planner Resource (iCPR). Users can view the extent of the potential damage, and explore key resources and critical infrastructure.[xiii]

The CBRN response community developed resources for understanding the scale of CBRN events. DOD, federal, and state agencies have tools and data repositories for their threat assessments.[xi] However, the outputs are often highly technical, requiring extensive expert translation and analysis to support command-level decision making. The result of using domain-aware AI in this mission space would provide a unified capability, collectively analyzing CBRN threats, infrastructure, and available resources for AI-generated decision-making products (Figure 3). A unified capability could include AI-enhanced terrain models for CBRN modeling, threat-aware navigation, and data-fusion for resource allocation. Additionally, traceable AI methods would decrease modeling time without significantly decreasing accuracy and would increase the responsiveness of DOD DSCA forces.

Figure 3. Conceptual Framework for using CBRN threat and damage assessment information to aid decision making during DSCA operations. Continuous threat assessment paired with multisource infrastructure data will result in decision aids for route planning, critical infrastructure identification, and automated resource tasking. (Figure generated by author)

Domain Aware Artificial Intelligence Opportunities

Existing domestic support operational tools can also mitigate U.S. force risks in hostile CBRN environments. CBRN threat-aware navigation tools will allow DOD forces freedom-of-movement even in the most austere CBRN environments. However, for a navigation specific application, commercial-off-the-shelf (COTS) AI algorithms may be insufficient. The AI tool must be aware of the domain implications of mission variables (mission, enemy, terrain and weather, troops available, time available, and civilian consideration) in addition to the CBRN threats when optimizing routes. For example, a non-aware AI tool may route all units through the same choke point without consideration of the negative impact of this channeling.

CBRN threat-aware reporting will also require many of the same AI advances that feed early detection of illicit nuclear material. Many of the high-fidelity CBRN modeling tools available to the DOD require 3D terrain details. While much of this data is readily available, there is often significant expert-level pre-processing required for use in the modeling tools. Application of domain-aware AI will enable rapid pre-processing of terrain and urban building data into the exact format needed for the modeling tools. The increased efficiency of data analysis allows experts to focus on model post-processing with associated higher quality decision-support products. Higher quality products directly support the commander's information needs for rapid and high-quality leadership decisions.

Conclusion

Operational AI enables efficient information discrimination within the context of unknown and unknowable situations while prioritizing insight over information.[12] Insight leads to a better understanding of the environment and clear military advantage. The use of AI is critical in characterizing a contaminated environment across time and space while precisely representing reasonable data. DNN R&D's advancement of domain-aware AI will yield a collection of methods and tools that are not just relevant for non-proliferation, but also for the full spectrum of countering WMD activities. The Army's use of domain-aware AI methods will identify and apply specific data needed in support of the instinctual leadership techniques employed by the battlefield commander. Ultimately, commanders continually analyze combat power described by the courage and competence of their Soldiers, excellence of their training in all CBRN environments, survivability of equipment within the environment, soundness of doctrine, and quality of unit leadership. Domain-aware AI increases commander decentralization of decision-making on the CBRN battlefield by increasing data discrimination and characterizing the real-time environment.

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Next-Generation Artificial Intelligence to Meet CWMD Challenges across the Four Cs

Ms. Angela Sheffield, Senior Program Manager, Data Science and Artificial Intelligence (AI)
Department of Energy (DOE), National Nuclear Security Administration (NNSA)

Leveraging the expertise of the DOE's National Laboratory Complex, NNSA's Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) drives the development of next-generation artificial intelligence (AI) methods and technologies to transform U.S. nuclear proliferation detection. Within DNN R&D, the Next-Generation AI portfolio works closely with U.S. government partners, including the DoD, to advance the state-of-the-art in AI for national security and transition AI-enabled technologies that enhance U.S. capability and readiness to meet nuclear nonproliferation demands. Next-generation artificial intelligence methods developed for nuclear proliferation detection can be leveraged by the U.S. Army to accelerate modernization and readiness in the CWMD mission space, specifically related to competition and change.

"Ready for what?"

Modern demands on the U.S. Army are far more than just conflict. In his article "The Question at the Center of Army Readiness: Ready for What?", U.S. Army Deputy Chief of Staff, G-3/5/7, Lieutenant General Charles Flynn describes a new framework that encompasses the totality of demands on the Army: in addition to conflict, this framework identifies competition, crisis, and implementing transformational change. Together, these "4Cs" chart the U.S. Army's path toward meeting multi-domain challenges, including those posed by WMD-capable adversaries.

The mission of the U.S. Army has traditionally been defined as preparing for and winning in conflict. However, recent events, including the coronavirus pandemic and nuclear modernization efforts, highlight additional demands for which the U.S. Army must be ready. In addition to conflict, these demands include long-term strategic competition with Russia, China, and emerging global powers; response to domestic and overseas crises; and implementing transformational change to modernize the force. This new framework expands requirements for readiness and modernization across the functions of the U.S. Army, in-

Ms. Angela Sheffield is the Senior Program Manager for Data Science and Artificial Intelligence at the Department of Energy (DOE) National Nuclear Administration's (NNSA) Office of Defense Nuclear Nonproliferation Research and Development. Ms. Sheffield has a B.S. in Economics from the United States Air Force Academy and a M.S. in Operations Research from Kansas State University. Prior to joining NNSA, Ms. Sheffield led project teams at DOE's Pacific Northwest National Laboratory (PNNL) to develop modeling and simulation and data science methodologies to inform CWMD policy and operations. Ms. Sheffield joined PNNL after a distinguished career as an Operations Research Analyst in the U.S. Air Force. She specialized in the research and development and technical intelligence of U.S. and adversary weapon systems. Her email address is angela.sheffield@nnsa.doe.gov.

cluding CWMD. As the Army implements the 4Cs within the CWMD mission space, it can leverage capabilities and approaches developed to support overlapping missions within the U.S. nuclear enterprise, including nuclear nonproliferation.

Working with allies and partners around the globe, the U.S. employs nuclear nonproliferation measures and programs to control the spread of nuclear weapons-usable capabilities; limit the production, stockpiling, and deployment of nuclear weapons; and decrease misperception and miscalculation to avoid destabilizing nuclear arms competition. Through measures including diplomacy, policies and treaties, threat reduction assistance, and export controls, nuclear nonproliferation seeks to dissuade or prevent state and non-state actors from proliferating nuclear-weapons usable capabilities or make more costly their access to sensitive technologies, material, and expertise.

Central to nuclear nonproliferation are technologies and science-based approaches to detect nuclear proliferation activities and predict and characterize the capabilities of existing and emerging nuclear weapons programs based on observable signatures and indicators. Nuclear proliferation detection technologies provide information to analysts and decision makers to enable nuclear nonproliferation programs and strategies for intervention. Proliferation detection is notoriously challenging. Indicators are sparse against a complex and noisy background. Methods must be extensible to new threats and suitable for uncooperative environments, which require clever approaches as assumptions required for traditional data analysis methods do not hold.

Advances in AI-enabled technologies and the availability of new data sources present new opportunities to transform U.S. nuclear proliferation detection. However, AI and analytics technologies developed by the commercial sector and classical data-driven approaches, including machine and deep learning, are insufficient for nuclear nonproliferation. DNN R&D is driving the development of the next generation of AI methods and technologies to build AI and analytics systems that are suitable for the challenges and requirements of national security missions.

DNN R&D's Next-Generation AI portfolio pursues complex, multidisciplinary research to advance the math and science of artificial intelligence and develop analytics suitable for national security missions. Rather than a single approach or technology, these missions demand innovative methods and highly specialized AI systems. DNN R&D is developing dynamic capabilities that provide more accurate information to operators, analysts, and decision makers to expand situational awareness, enhance sensemaking, and enable data-driven decisions. These computational technologies reduce the hands-on time and effort required by an operator or analyst, providing them more time to support other mission demands.

Within the U.S. nuclear nonproliferation and nuclear security enterprise, nuclear proliferation detection requirements overlap with the demands of U.S. Army CWMD missions. Within these areas of overlap, Next-Generation AI technologies and approaches developed for nuclear proliferation detection can be leveraged to support the U.S. Army's CWMD readiness, particularly in WMD competition and as the U.S. Army changes to modernize its CWMD force.

Competition in the CWMD Domain

Competition recognizes that demand for U.S. Army readiness is driven by long-term, strategic competition with China and Russia. Within existing nonproliferation and counterproliferation programs, the U.S. implements policies, programs, and activities to ensure capability and influence relative to China and Russia and identify emerging WMD programs. For example, procurement interdiction programs impose entity- and transaction-level costs on adversaries while measures like economic sanctions, policies, and treaties apply long-term, strategic disruption to their WMD programs. The United States implements programs like the mid-20th century Atoms for Peace and modern-day scientific exchanges with South Korea and Japan to build international alliances and strengthen American influence for nuclear and WMD science and security.

Next-Generation AI technologies may enable detection of strategic changes in the intent of foreign nuclear programs earlier than has ever been possible to inform U.S. competition with Russia and China. They also reveal insights about the sophistication and capability of foreign nuclear weapons programs to strengthen U.S. CWMD missions in conflict. Where possible, the U.S. Army should leverage insights provided by Next-Generation AI methods and technologies to guide CWMD readiness and modernization for competition with China and Russia.

Next-Generation AI for Competition

Many nuclear proliferation detection technologies currently used by the United States monitor for the use of specialized nuclear material and equipment unique to nuclear weapons development. Leveraging advances in data science and computing as well as new data sources, DNN R&D's Next-Generation AI portfolio is developing innovative, AI-enabled techniques to reveal additional indicators of nuclear proliferation. These next-generation methods reveal subtle clues that may indicate change in capability or strategic intent of foreign nuclear weapons programs.

In one example, Next-Generation AI technologies developed by the multi-laboratory Advanced Data Analytics for Proliferation Detection (ADAPD) project track the progress of foreign scientists engaging in nuclear weapons-related research to reveal indicators of change in capability earlier than has ever been possible. This insight, revealed during competition rather than conflict, affords the United States more options for intervention and readiness.

In another example, Pacific Northwest National Laboratory is developing an AI system to analyze a vast dataset from multiple agencies to discover illicit procurement by foreign companies trafficking nuclear weapons-usable equipment to inform U.S. response and interdiction within the global commercial sector. This modernized capability enables analysts to exploit intelligence at a scale previously out of reach and has revealed key leads months earlier than existing approaches.

Seeing Through the Fog of Competition

Readiness for the demands of competition requires accurate assessment and continuing reassessment of an adversary's abilities, capabilities, and vulnerabilities and the related effectiveness of U.S. capabilities, a notoriously challenging task. Within the CWMD mission space, there are very few observable indicators of change within an emerging or sophisticated nuclear program. Signatures of these indicators are faint against a complex and noisy background. Adversaries disguise their activities to advance or expand their capability or influence.

Research within the Next-Generation AI portfolio is focused on advancing the mathematics and science to assess adversary capability despite the challenges of the competition regime. The Next-Generation AI portfolio is developing flexible techniques to combine heterogeneous data sources, modeled predictions, and machine learning to increase sensitivity to faint signals of interest and augment sparse datasets. Additionally, the portfolio is developing techniques to leverage advances in data science and new data sources to reveal early indicators of nuclear proliferation from large and unstructured data.

The most successful capabilities developed by the Next-Generation AI portfolio are not static technologies. They are systems of models and advanced data analyses that are employed dynamically by operators and analysts. They are responsive to new threats, extensible to emerging issues, and suitable for the fog of competition. One single AI technology or analytic technique will never address the full range of data sources and operational demands in the CWMD mission space.

Figure 1. Advances in AI-enabled technologies and the availability of new data sources present new opportunities to broaden U.S. nuclear proliferation detection, enabling early detection of emerging nuclear weapons threats and revealing insights about the sophistication and capability of existing foreign nuclear weapons programs to strengthen U.S. capability in *competition* and *conflict.*

Change: Accelerating CWMD Modernization and Readiness

The methods and technologies developed by the DNN R&D Next-Generation AI portfolio are well-aligned to the needs of a modern U.S. Army CMWD force. Specifically, these technologies can be leveraged to inform calibrated force posture and develop integrated systems suitable for multi-domain operations. Leveraging the capabilities developed by the Next-Generation AI portfolio will accelerate the Army's change to be ready for the future, realizing readiness sooner and more efficiently.

Next-Generation AI for Calibrated Force Posture

AI and analytics are paramount to achieve calibrated force posture. General Flynn explains that calibrated force posture is an essential element of Multi-Domain Operations that ensures the Army is in the correct position to meet simultaneous demands to compete with adversaries, respond to crises, and win in conflict. The requirements for AI systems for calibrated force posture are similar to those for nuclear proliferation detection. Both require capabilities that produce more accurate and higher-resolution information than existing methods. They must be extensible to new threats, suitable for uncooperative environments, and perform predictably in uncharacterized settings. They require techniques to support decision making with quantifiable uncertainty. In developing methods and techniques that meet the demands of nuclear proliferation detection, the Next-Gen AI program has developed capabilities that will enable calibrated force posture during competition and conflict.

For example, the multi-Laboratory ADAPD project is developing new techniques to analyze pattern-of-life data and data from foreign nuclear weapons tests to determine the sophistication of the nuclear weapons programs. These techniques may reveal insights into a country's nuclear doctrine and to inform the posture of the U.S. Army's forces in competition.

In another example, Sandia National Laboratory developed a custom AI framework to characterize detonations in denied-access locations. Mathematically, modeling and advanced data analysis methods suitable for contested environments require entirely different approaches than traditional applications. This technique produces more accurate assessments and requires a fraction of the data required by current methods, demonstrating the potential extensibility of this methodology to inform calibrated force posture analyses in conflict. This technology transitioned to a DoD mission partner.

Next-Generation AI for Multi-Domain Operations

Enhancement to nuclear proliferation detection requires multi-domain approaches. The methods developed by DNN R&D leverage data, information, and mission capabilities from multiple domains. These techniques will provide solutions that enable rapid and continuous integration of multi-domain data for a range of CWMD missions.

Sensor data fusion requires sophisticated mathematical and computer science approaches. Current methods are typically not reusable. DNN R&D's Next-Generation AI portfolio is building out the science of data fusion and piloting new procedures for producing and managing sensor data that is suitable for a multi-domain task force, where sensor fusion is the new paradigm.
For example, researchers from across the Laboratory Complex are developing techniques to fuse data from air-, land-, maritime-, space-, and cyberspace-based sensors to provide improved assessments of adversary operations of WMD capabilities. They have also developed procedures and data management systems to facilitate multi-modal data fusion as well as mathematical and engineering techniques to synchronize datasets collected from multiple sources.

Convergence: Taking the Research to the Mission

The development of AI systems to transform U.S. nuclear proliferation detection requires focused research in the toughest areas of science with tight alignment to mission demands. This is more than a philosophy – it defines the DNN R&D's Next-Generation AI strategy and day-to-day research and development agenda. DNN R&D works closely with partners in the U.S. CWMD enterprise, including the U.S. Army, to understand needs and operational constraints to advance the right science and develop innovative capabilities. Next-Generation AI portfolio project teams understand mission partners' requirements for new technologies and how operators and analysts will use them to design reliable and interoperable systems.

This partnership extends throughout the lifecycle of the project to support mission partners' transformation from current capability to a modernized force. In Interagency forums and working groups, the Next-Generation AI portfolio advances the practice of analytics for national security and informs U.S. policy on CWMD and emerging technologies. Additionally, DNN R&D's Next-Generation AI portfolio implements the practice of early and incremental delivery of new technologies. While these technologies are only components of the full system, incorporating these components incrementally over time accelerates change through modernization to an AI-enabled and ready force capable of meeting future challenges in competition, conflict, and crisis.

Conclusion

As partners within the U.S. CWMD enterprise, DNN R&D's Next-Generation AI portfolio and DoD CWMD forces are aligned to the same aim point. While the capabilities developed by the Next-Generation AI portfolio are focused on nuclear nonproliferation, the U.S. Army can directly leverage these methods and technologies to address CWMD demands – and U.S. Army missions more broadly. The U.S. Army should draw on the technologies and strategies developed by DNN R&D's Next-Generation AI portfolio to address demands in competition and to accelerate readiness as the force changes to the future operating concept, Multi-Domain Operations.

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U.S. Army Lab Explores Artificial Intelligence / Machine Learning Potential in Development of Chemical Biological Defense Solutions. by Jack Bunja, identified by DVIDS

Tactical Nuclear Wargaming: An Innovative Approach to Conventional Nuclear Integration Techniques

Miles Paca, CPT U.S. Army National Guard
Research Scientist I, Georgia Tech Research Institute (GTRI)

Matthew Mahoney
Defense Threat Reduction Agency Research and Development - Nuclear Technologies Assessments (DTRA RD-NTA)

Sharaé Meredith, PhD
Senior Research Engineer, GTRI

John Brittingham, CDR USNR, PhD
Principal Research Engineer, GTRI

Robert Pritchard, LtCol USMCR (Ret)
Research Engineer II, GTRI

Greg Louden, LTC USA (Ret)
Principal Research Engineer, GTRI

Introduction and Background of Conventional Nuclear Integration Wargaming

The current requirements for CWMD preparedness across all levels of the Joint Forces have led to focused initiatives in the realm of nuclear weapons defense planning, training and exercise[1]. Techniques like military wargaming for putting such initiatives into action are of critical importance to addressing the centralized concepts of nuclear defense and deterrence. Conventional Nuclear Integration (CNI), a concept referring to the side-by-side operation of nuclear and conventional forces referenced by Kinman[2], is a field of nuclear defense strategy that includes nuclear weapons employment on the battlefield. Though not always expressly grouped under the umbrella of CNI, military wargame exercises which could be considered within the subset of CNI have provided insights into operations on the nuclear battlefield since the Cold War era.

Most often, the term "nuclear war" elicits images of large-scale nuclear weapons delivered from intercontinental-range weapons against strategic targets. Though highly beneficial to examine these kinds of conflicts in a wargame, these are not exclusively the only kinds of nuclear conflict the United States and its allies could face. Non-Strategic Nuclear Weapons (NSNW) - also known as tactical nuclear weapons - are a broad class of weapons not well defined but generally categorized as "short-range delivery systems with lower-yield warheads that might attack troops or facilities on the battlefield"[3]. Delivery systems like tactical missile launchers capable of delivering NSNW's are generally outside the regulatory scope of nuclear arms control[4], and the recently extended New START Treaty between the U.S. and Russia currently only regulates ICBMs, SLBMs and heavy bombers, leaving a critical gap of unregulated nuclear arms[5]. Several additional "near peer" states are known to possess significant tactical nuclear weapon arsenals, and efforts are being made by regional potential threat nations to develop tactical nuclear weapons programs[6]. In January 2021 North Korean dictator Kim Jong Un stated: "We must develop tactical nuclear weapons that can be applied in different means in the modern war depending on the purpose of operational missions and targets"[7].

Clearly, the threat of tactical nuclear weapons employment on a battlefield is a consideration that must be taken into account. Allied Joint Forces must be prepared to conduct operations in a nuclear contested environment and to mitigate the effects of nuclear weapons on such operations across all levels of war. This also implies that nuclear weapons use must not be considered a game-ending event in simulations and tactical exercises. Unique strategies like CNI wargames to train commanders and staffs to respond to a nuclear detonation (NUDET) must be implemented in order to ensure the U.S. is prepared to succeed in the nuclear operational environment.

With these considerations, the Defense Threat Reduction Agency (DTRA) has pursued CNI initiatives through collaboration among multiple organizations with critical capabilities related to CBRNE. The DTRA Research and Development (RD) Directorate is working with organizations such as the Georgia Tech Research Institute (GTRI), Federally-Funded Research and Development Centers (FFRDCs), and industry to conduct focused research regarding nuclear weapons effects and their implication on the battlefields of the future.

Miles Paca is a Research Scientist I Georgia Tech Research Institute in Atlanta, GA. He has a B.S. in Biology from Georgia Tech. His email address is miles.paca@gtri.gatech.edu.

Matthew Mahoney is Senior Technical Manager at the Defense Threat Reduction Agency, in Fort Belvoir. He has a B.S. in Mechanical Engineering from Virginia Tech, M.S. in Operations Research from George Mason University. He was previously assigned as a Senior Consultant at Deloitte Consulting. His email address is matthew.j.mahoney18.ctr@mail.mil

Dr. Sharaé Meredith is a Senior Research Engineer,at Georgia Tech Research Institute in Atlanta, GA.

Dr. John M. Brittingham is a Principal Research Engineer at Georgia Tech Research Institute in Atlanta, GA. He has a B.S. in Physics from Yale University, a Juris Doctor from University of Memphis, and a Ph.D. in Nuclear Engineering from the University of Tennessee. His email address is john.brittingham@gtri.gatech.edu.

Robert Pritchard is the Wargaming Lead in the Analytics and Wargaming Branch at the Georgia Tech Research Institute (GTRI) in Atlanta, GA. He has a B.S in Aerospace Engineering from the U.S. Naval Academy. He was previously assigned as a Joint Cell Officer and Exercise Control Officer at the Marine Corps Tactics and Operations Group (MCTOG), Twentynine Palms, CA. His email address is robert.pritchard@gtri.gatech.edu.

Gregory Louden LTC (Ret), is the Interim Chief of Advanced Warfighting Technologies Division at GTRI in Atlanta GA. He has a B.S. in Mechanical Engineering from Georgia Institute of Technology. He was previously assigned as a, FA52 DIA, Joint Staff, DTRA, USFK. His/her email address is __gregory.louden@gtri.gatech.edu

That research includes integration with organizations such as the US Army Nuclear and Countering Weapons of Mass Destruction Agency (USANCA), Joint Program Executive Office for Chemical, Biological, Radiological and Nuclear Defense (JPEO-CBRND), and Program Executive Office Simulation, Training and Instrumentation (PEO STRI), among others. In June 2020, GTRI was tasked to provide DTRA with the nuclear technologies technical support to recommend the conditions to institutionalize CNI across the joint forces – specifically with respect to wargaming at the tactical level for ground maneuver forces in the Army and Marine Corps. This led GTRI to begin development of a ground-based wargame for refining techniques and approaches to CNI wargaming. GTRI began the effort by focusing on baseline development with the One Semi-Automated Forces (OneSAF) simulation.

Figure 1: Artistic Rendition of Tactical Nuclear Weapon's Impact on Maneuver WfF

CNI Wargame Development

In the first iteration of wargame development, GTRI made strides with the aid of active duty U.S. Army collaborators to develop a useful scenario that addressed and integrated the tactics, techniques and procedures (TTP's) used at a tactical level – specifically, to fight through a nuclear operational environment (OE). The commander and staff from a U.S. Army Stryker Infantry Battalion participated remotely in a virtual wargame with the commander and each of the staff sections performing their respective roles in executing the operations process of a movement-to-contact mission that was consistent with the Mission Essential Task List (METL) for this maneuver battalion.

The scenario focused on the conduct of a large-scale ground combat operation with key objectives and a specified end state. The participants took the role of "blue forces" and were challenged with the Mission, Enemy, Terrain & Weather, Troops and Support Available, Time and Civil Considerations (METT-TC) consistent with an Eastern European conflict in the Baltics. Opposing the BLUE Force was a live, thinking "RED force" familiar with the deployment, weapon systems, tactics, and employment of threat forces. The RED forces replicated a near-peer competitor. "RED forces" had their own set of objectives and a clear end state towards which they were working; current and former active duty maneuver leaders performed these roles. A "WHITE cell" served as a referee, an operator/controller for simulation inputs, and as role-players of the BLUE Force Battalion's higher, adjacent, and subordinate units for key scenario injects into the wargame. The benefit of this format was that it replicated the type of wargame setup with which participants were familiar, enabled the focus on specific objectives related to nuclear effects, and elicited the operating forces' active participation in the experiment.

Prior to the start, participants were given a pre-mission scenario framework and briefings on "Road to War", a Concept of the Operations (CONOPS), and Nuclear Weapons Effects. The CONOPS brief included specific elements from the Military Decision Making Process (MDMP) which had been completed prior to the event by exercise support staff. These CONOPS included the planning process derived mission and "task and purpose" for executing the operations process at the battalion echelon of command. The battalion commander and staff were equipped with the standard Table of Organization and Equipment (TO&E) for a task organized Stryker Infantry battalion exercising command and control (C2) over subordinate units on the battlefield, coordinating fires, and seizing key objectives. The challenge of the wargame was to assess how the integration of nuclear weapons effects could impact the execution of the mission and to introduce a new level of complexity to ground maneuver operations. For clarification of these effects, blue force participants received a pre-wargame brief on the impact of nuclear weapon effects by a subject-matter expert and were advised of the range of possible impacts of nuclear threats present in the game. This brief focused on the immediate and mid-term effects that would be experienced by a unit at a close, intermediate, and long-range distance from a tactical NUDET. The focus centered on the impact upon operational decision making for units and personnel which were at a survivable distance from ground zero. The brief compared various yields for better understanding of the relative power of a nuclear weapon on the battlefield (especially in comparison to conventional weapons), including the fallout hazards and radiation effects on personnel.

To enable a tactical wargame with nuclear weapons, the wargame must incorporate the effects of a NUDET with sufficient fidelity to provide realistic outcomes based on factors such as the type of weapon, the height of burst, the type of equipment, and the distance of the equipment from ground zero. Detailed equipment vulnerability analyses may exist for the equipment in question; however, these vulnerability analyses are generally classified and may not be available for a wargame conducted at the unclassified level. While classified models may increase fidelity and may be necessary depending on the wargame's purpose, this level of accuracy and fidelity does not constitute a prerequisite to wargaming the tactical nuclear battlefield effectively. Generic nuclear devices and a hierarchy of equipment survivability can substitute for these detailed models, relying only on unclassified models and information found in publications such as Glasstone and Dolan[8]. Using the physical parameters from Glasstone and Dolan, combined with simplified survivability assumptions, the wargame can proceed effectively.

The prime factor that enables effective wargaming with "good enough" models lies in the physics inherent in the propagation of prompt nuclear effects such as air blast, thermal radiation, and prompt ionizing radiation through the environment. As these effects spread from the point of burst, their strength will decrease both due to the dispersion of the effects (e.g., inverse square law) and due to the attenuation of the effects in the atmosphere (e.g., due to scattering and absorption of the radiation). Consequently, the distance between points in space where the probability of survival from the prompt effects is almost nil to points where survival is nearly certain is typically less than a few hundred meters. Figure 2 shows the relative strength of the effects from a 1kT and 10 kT tactical nuclear weapon as a function of distance from ground zero, illustrating the relatively short distance over which the effects will diminish.

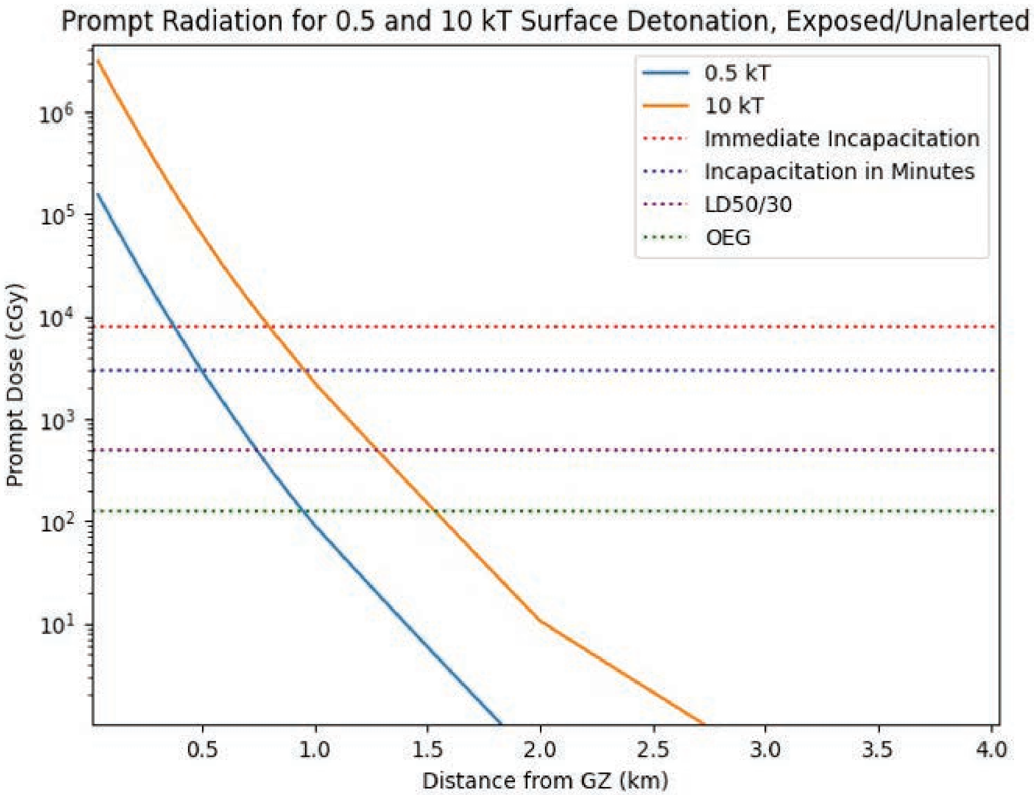

Figure 2: Example of Prompt Radiation Dose Calculation for Dismounted Personnel for Near-Surface Fission Weapon Burst

As a result of these modeling considerations, the GTRI project team was able to immerse the BLUE force participants into a series of tactical challenges against a free playing RED force with realistic tactical nuclear weapons effects.

CNI Wargame Execution

With a duration of approximately two hours, execution of the wargame consisted of continuous play between opposing RED and BLUE forces in simulation with participants notifying the WHITE cell regarding tactical decisions to input into the OneSAF simulation. The design of the wargame allowed all members of the unit's staff to exercise their respective functions and engage a subset of their staff battle drills and dynamic decision-making while on the nuclear battlefield. This open look at the staff processes and decisions added a key functionality to the wargame and gave researchers valuable insight into the operations, intelligence, planning, logistics, personnel and communications considerations and challenges that ground maneuver forces face in a nuclear OE.

As the simulation introduced nuclear effects into the environment, participants were challenged to assess and respond to resultant hazards. Leaders were presented with situations requiring them to address the consequences of nuclear detonation and its impact on operations. As the staff engaged in battle management processes, analysis could be focused on the areas of most significance to ground maneuver warfare to facilitate development of the techniques for systemization of CNI wargaming.

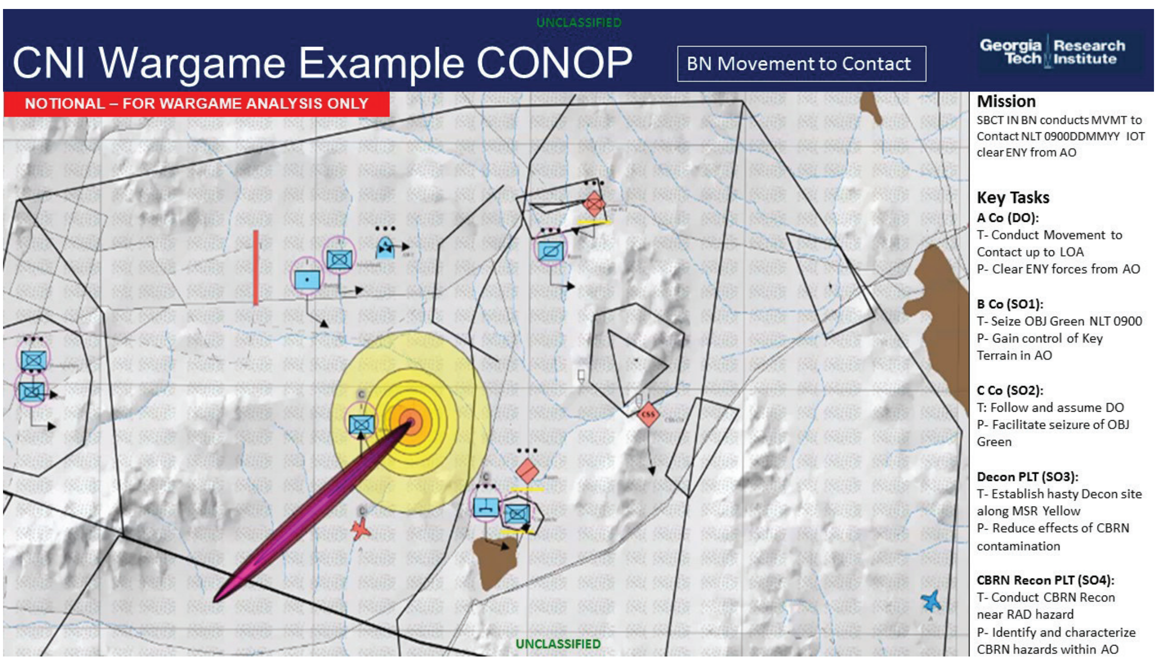

Figure 3: Example CONOP of CNI Wargame (notional, for training and analysis only)

To aid the situational awareness and modeling of nuclear events, the CBRN Warning and Reporting System (CBRNWRS) was integrated into the BLUE force's common operating picture as a layer of technique development. Rapid reporting of a nuclear event and modeling of the resultant hazard area is critical to ensuring the safety of personnel and continued operations. Integration of the CBRNWRS allowed researchers to study the commander and staff's abilities to quickly process and interpret CBRN reports and to recognize the systems and approaches of CBRN consequence management. The battalion commander was able to use information from the CBRNWRS to execute informed decision-making and direct CBRN response activities.

Observation of tasks such as radiological reconnaissance, decontamination, and evacuation of radiation exposed personnel provided researchers and subject-matter experts a clearer understanding of the decision driving points, motivations and thought processes commanders utilize to reach the desired end state and achieve outcomes in a nuclear OE. Due to a lack of attention given to nuclear threats at the tactical level in many years, this view of the operational decision-making provided valuable information and insight on commander and staff reaction to adversarial employment of nuclear weapons on the battlefield. CNI Wargame designers expect to utilize the analysis of these decisions and capture of the results in a data repository to subsequently support development of improved CWMD decision-making processes and response methodologies.

CNI Wargame Data Analysis

Research continues after the wargame with the analytical evaluation of information collected from the event. Details emerge in two forms: (1) capabilities/limitations of the simulation environment, and (2) the impacts on decision making that are unique to the nuclear OE.

It is important to have a sober and healthy understanding of the capabilities and limitations of the simulation environment because it has a direct impact on the decision-making process. Without a proper reference, it is easy to be led astray by the analytics of the post-processed data that tends to have a heavy emphasis on the outcome of the event. Therefore, as the wargame is performed, evaluations and assessments are made based on participant observations and feedback. This highlights the significance of having individuals reprise roles within the simulation environment that are consistent with their military duties. Such individuals are able to provide insight on the expectations of available and retrievable data during operations on which they rely to make sound decisions and judgements. Furthermore, their input identifies limitations in the simulation environment that may skew perception of the nuclear OE, generating a false narrative. This is a critical point of consideration when evaluating the viability of the simulation framework.

The second aspect of data analysis focuses on the decision-making required to complete a mission objective. The degradation of combat power, deterioration of supplies, and impact of radiological hazards all provide a conceptual view of the state of the "BLUE" and "RED" forces in the midst of a wargame. Coupling these details temporally provides a timeline that documents the decisions made and the corresponding outcome. Quantitative measures of the wargame enable diagrams and charts to be generated that show trends of where specific decisions have an impact within an event. It is through data analytics of these findings that tactical decision-making can be optimized to increase the probability of success of a mission within a defined environment. Increasing the number of iterations of that event, where a defined set of variables is dialed up or down to generate operational changes in a scenario, will provide a greater technical envelope of measured data. Statistical analyses are performed to determine strengths, vulnerabilities, and opportunities for improvement when evaluating the decision making in the nuclear OE. With the two defined approaches for data analysis, GTRI is able to provide DTRA with measures of effectiveness and performance of both the simulation environment and the wargaming techniques.

Using this effort as a baseline step, DTRA and GTRI plan to create an increased level of quantitative assessment and visualization in the second and subsequent iterative development cycles in nuclear weapons effects based wargaming. This process of development will allow rapid, meaningful, and accurate information to be delivered to participants of future wargames regarding the effects generated by a tactical nuclear weapon. This information will be integrated into the C2 process to be transformed into understanding that will enable better informed decision-making in the nuclear OE by the commanders and staffs at the various echelons of command at the tactical to operational level.

CNI Wargame Conclusions

Figure 4: Active U.S. Army Battalion Staff Personnel Participating in the Wargame Simulation

Discussions from the after-action review brought out key lessons learned and elicited dialogue among soldiers in the virtual command post and the wargame designers, facilitators, and SMEs. Participants indicated that as a result of the wargame they were more informed about the nuclear operating environment and the impact of nuclear weapons effects upon their operations process. The dialogue enabled by the wargame highlighted the relevance of the DTRA-led effort to institutionalize an understanding of CNI across the Joint Force. Additionally, the immersion of the operators into the simulation-based nuclear battlefield within the context of a force-on-force wargame facilitated by subject matter experts elicited the desired focus on this problem set throughout the four hours of the CNI event. In particular, participants commented on the informative nature of the nuclear effects brief by subject-matter experts; few of the staff had been trained on their effects in the context of operational maneuver. This point brings to light a known key shortfall in current military education - as discussed by Kinman - and offers a path for targeting potential solutions to this issue[2]. In the long-term approach to CNI, nuclear wargaming should be considered a viable tool for educating Joint Forces regarding the decisions and challenges faced for operational maneuver in a nuclear environment.

Following the exercise conducted with the U.S. Army Stryker Infantry Battalion and first phase of development, several refinements were implemented to the wargame technique. CBRN capabilities briefs were added to give non-CBRN specialty participants a stronger understanding of CBRN operations. Wargame designers refined the pre-mission briefings to mirror more closely the MDMP process and model pre-scenario briefs similar to those briefings given in U.S. Army battle labs. Nuclear weapons effects and radiation hazard dispersion models were updated in OneSAF using the Hazard Prediction Assessment Capability (HPAC) to generate a more realistic nuclear hazard visualization. Graphic overlays of these models will be available to participants in future experiments.

Forthcoming iterations of CNI wargame development will explore a greater degree of integration of data analysis into the simulation and fine-tuning of the visualization of effects of nuclear weapons within the game. Several process refinements will be made similar to processes employed by DoD battle labs, such as the U.S. Army Maneuver Battle Lab at FT Benning, GA., which utilize well developed methodologies for experimentation and problem analysis using the latest versions of currently employed Modeling and Simulation tools[9]. Similarly, these experimental concepts have been demonstrated in nuclear wargames, such as SIG-

NAL, which quantitatively analyzes nuclear decision making at the strategic-level[10]. While data analysis in wargaming has clearly proven useful elsewhere, the concept of quantitative wargaming at the tactical level is still an area requiring much development. In-depth analyses of quantitative data from simulations will enable greater insight into key decisions and processes that generate useful outcomes for research application.

DTRA and GTRI, by continued and expanded integration across the relevant CBRN and M&S organizations, including DoD/US Army, FFRDCs, and industry, expect to engage a wider audience of Joint Force maneuver units to expand scenarios and address the issue of decision-making within a nuclear OE. In light of the current threat of tactical nuclear weapons on the battlefield and the DoD's shifted focus towards CNI, it is prudent to begin exploring the approaches and techniques to pass along vital knowledge of various aspects of nuclear integration to the next generation of warfighters. Through facilitated work with ground maneuver collaborators, our trajectory is aimed at refining the development of these techniques to fully support the institutionalization of CNI across the Joint Forces.

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Among the smallest of the weapons in the Army's nuclear arsenal was the M28/M29 Davy Crockett, a recoilless rifle system operated by a three-man crew it entered into service in the early 1960s (Photo provided by Los Alamos National Laboratory Historical Department).

Six Myths About Nuclear Weapons

Mr. Keith Sloan
United States Army Nuclear and Countering WMD Agency (USANCA)

With the release of the 2018 Nuclear Posture Review[i] and Secretary of Defense (Sec Def) pronouncements declaring the Nuclear Enterprise the top priority for DOD[ii], nuclear weapons have rapidly returned to the center stage of debate on security. However, recent discussions of nuclear weapons policy are riddled with error. Myths and misconceptions fueled by 75 years of pop culture abound, seriously undermining a true understanding of these weapons, their effects, their place in strategy, and implications for national security in the post-Cold War world. This article seeks to dispel the most significant, widespread, and persistent misconceptions surrounding nuclear weapons in order to lay a better foundation for the analysis of nuclear implications for modern warfare. It is not intended as an advocacy piece but rather to level the playing field of knowledge to better inform future debate. I discuss these six persistent myths and misconceptions when teaching the DoD's only joint training course focused on nuclear operations in a theater context.

Current U.S. nuclear policy starts with the basic assumption that the most likely use of a nuclear weapon is as a result of escalation in a regional conflict, rather than the classical "massive exchange" scenario of the Cold War. Indeed, the current era does not map well to the Cold War. Instead, the United States and its allies and partners are faced with regionally focused adversaries (Russia, China, and North Korea) that are nuclear-armed and with whom the threat of future conflict exists. In the event of a regional conflict with a nuclear-armed state, there exists a non-trivial chance that one (or both) sides might employ nuclear weapons to achieve a military or other advantage. Such use of nuclear weapons would not end the underlying regional conflict but would merely complicate it. For instance, if Russia were to invade the territory of a NATO nation, the Alliance's goal would be to expel the invaders. If Russia were to use a nuclear weapon in such a conflict, the goal of expelling Russia from NATO territory would not fundamentally change; it would assuredly become a more complex problem. This underlying assumption has numerous implications for the myths to be addressed.

Keith Sloan is a Nuclear Target Integrator with the U.S. Army Nuclear and CWMD Agency (USANCA). Keith has a BA in Political Science from the University of San Diego, an MA in International Relations from Creighton University in Omaha, Nebraska, and an MA in Homeland Security and Terrorism Studies from American Military University. His previous experience includes a career as a submarine warfare officer in the United States Navy and a CWMD Strategy and Policy Specialist with Headquarters, U.S. Army. In addition to submarine assignments, he served as an intelligence analyst at the Office of Naval Intelligence, a nuclear strike advisor aboard U.S. Strategic Command's airborne command post, and as chief of a nuclear arms control inspection team at the Defense Threat Reduction Agency. His email address is keith.a.sloan.civ@mail.mil..

Myth #1: Nuclear weapons will never be used in warfare. Nuclear weapons have, of course, been used in warfare before. However, there is a perception that this will never occur again, especially in the context of a "limited" regional conflict because of the dangers of uncontrolled escalation. And if there is little likelihood of nuclear use, why bother with preparing for it in the first place? That mindset is not the perception of potential adversaries. Russia, in particular, has made it clear that they would consider nuclear weapons use to end a conflict on their terms, sometimes referred to as escalate to deescalate.[iii] Indeed, Russia continues to train its forces to operate on a nuclear battlefield, as witnessed by its extensive Grom-2019[iv] exercise, which included simulated nuclear strikes by all three legs of Russia's nuclear triad as well as non-strategic nuclear forces, significant ground force participation, and the direct involvement of Vladimir Putin.[v] Clearly, Russia views this as a possibility, given its extensive investments in nuclear arms and willingness to spend precious resources on training for it. Russia also seems to differentiate between strategic use of nuclear weapons and theater use,[vi] something the United States tends not to do. North Korea's policy is less clear, but the fact they have built a credible nuclear program[vii] under conditions of economic austerity certainly would seem to indicate that they would use such weapons in a conflict, as they would likely view any conflict as a threat to regime survival.

Myth #2: U.S. commanders would never feel the need to use a nuclear weapon due to U.S. conventional superiority. While potential adversary first use is the usual expectation, the possibility also exists that a U.S. commander might be faced with a need to request an effect that requires a nuclear weapon in extreme circumstances, prior to any adversary use of such a weapon. While the United States does have a significant conventional superiority, those forces may not be massed in the location of a regional conflict. In the event of regional conflict, the United States and its allies would defend with the forces already present while the United States would flow forces to the theater to build combat power over time in preparation for shifting to the offensive. Potential adversaries realize this and will certainly try to prevent the United States from moving forces into theater. This could leave those limited friendly forces facing adversaries with regional conventional superiority. In extremis, a U.S. commander could ask for an effect that would require a nuclear weapon to prevent a unit from being annihilated by an adversary. There is a reason that the United States does not have a "no first use"[viii] policy. The most recent Nuclear Posture Review explicitly states that the United States might respond to a non-nuclear strategic attack with nuclear weapons.[ix]

Myth #3: If nuclear weapons are used, they would rapidly terminate or negate the regional conflict. This is the "easy button" that planners and staff have pushed for decades when exercising scenarios that involved nuclear use. If a nuclear weapon is used by an adversary in a regional conflict, many believe that the response would be owned by U.S. Strategic Command with the theater commanders more of a spectator as would occur in a "massive exchange" scenario. But, as stated above, the truth is that the underlying regional conflict does not end and the theater commander's objectives remain, albeit complicated. Many historic U.S. exercises and wargames introduce a nuclear detonation and the exercise ends. That leaves the United States and its allies and partners unprepared for what comes after the actual event. Additional and more frequent exercises including "what next" aspects in response to an adversary nuclear weapon use or non-nuclear strategic attack, including continued operations in a nuclear environment, escalation control, political ramifications, and the like would aid in readiness against a nuclear-armed adversary.

Myth #4: Nuclear weapons will result in clouds of radiation that will make large areas uninhabitable for centuries and unsuitable for continued military operations. There is a perception that any nuclear explosion will result in large quantities of radioactive fallout, but this is not necessarily true. Nuclear detonations where the fireball does not touch the earth, referred to as air bursts, result in relatively minimal quantities of radioactive material, certainly levels far below what would impact military operations. Even with strikes that produce fallout, that radioactive material decays to levels below what would be considered militarily significant in a matter of days, not centuries. A good example of an airburst would be Hiroshima, which recovered in a few years[x] and has been a thriving city for many decades not unlike cities firebombed with conventional munitions. In Nevada, the United States detonated nearly a thousand weapons[xi] – it is perfectly safe to walk around most locations there today with no radiation concerns whatsoever. Related to this is a perception that the destruction from a nuclear strike against military forces would be vast. This is true – if the targeted forces are concentrated geographically. But on a modern battlefield, dispersion is crucial for survival against integrated conventional fires, as has been observed in the Russia-Ukraine conflict.[xii] Such dispersion mitigates nuclear effects, as well.

Myth #5: The United States is adequately prepared to fight on a nuclear battlefield. Widespread acceptance of the previous myths has resulted in a U.S. military that is underprepared to fight against a nuclear-armed adversary on what could become a nuclear battlefield. For example, the last time doctrine for operations under nuclear conditions was updated was 1996 and while the doctrine exists in archive, it is not considered current. Doctrine drives training and exercises meaning DoD has limited training and exercise opportunities to teach and evaluate its ability to operating on a nuclear battlefield. Professional Military Education (PME) on nuclear topics also needs improving.[xiii] The fact that adversaries like Russia intensively prepare for operating on a nuclear battlefield while the United States and its allies do not could serve to incentivize adversary nuclear weapons use in a limited regional conflict. Readiness to fight on a nuclear battlefield supports U.S. nuclear deterrence posture.

Myth #6: Nuclear warfighting is the province of specialty, CBRN forces. Operating on a nuclear battlefield is a whole of staff problem and nuclear effects impact every staff section. It is not for CBRN specialists to assess or manage impacts to sustainment or ISR, for instance. Rather, all staff sections must understand nuclear impacts to their functions. As a corollary, nuclear readiness is a whole of Service problem, as well. Readiness cannot be relegated to a single branch or specialty, but the implications of nuclear warfighting must be incorporated throughout every Service, from basic training, to PME, planning, training, exercising, etc. The Air Force, for instance, has recognized that they are seriously bifurcated between a "nuclear Air Force" and a "conventional Air Force." This bifurcation results in integration challenges at operational and tactical levels. At first publication, the U.S. Army's centerpiece concept, Multi-Domain Operations (MDO),[xiv] included a statement that MDO was not applicable in a conflict where nuclear weapons are used. That statement has since been corrected in follow-on explanations of the concept. When fighting a nuclear armed adversary, the thought that the conflict will remain either conventional or once it goes nuclear, stay nuclear, is no longer a valid way of thinking. Nuclear-conventional is not an either-or relationship. Conventional-nuclear integration (CNI), is an important priority for the Services and the Joint Force.

These six myths remain endemic across the Joint Force. However, the probability of nuclear weapons use on the battlefield is a reality that can no longer be ignored. Ignoring possible nuclear weapons use and its implications can only hurt the United States and its allies in a conflict against a nuclear armed adversary by leading to uninformed decision making, confusion, and paralysis. Not preparing, perversely, could lead to the use of such weapons by an adversary to counter U.S. conventional superiority with the intent to exploit perceived lack of U.S. readiness to operate in that environment. Expensive material solutions have been debated and are largely being funded,[xv] but also needed is increased funding and, most importantly, emphasis to advance less tangible (and less expensive) solutions of education and training.

As DOD modernizes its nuclear enterprise and readies forces to deal with the employment of nuclear weapons on the battlefield, resourcing and priority decisions need to be grounded in a solid understanding of nuclear weapons, their effects, and the implications of their use in a theater conflict. Awareness, education, and training are the starting points for change. Fortunately, the author is witnessing a slow awakening across DoD.

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Hardtack 1 Oak182K was conducted 29 Jun1958 in very shallow water (12 feet). This bomb design was later developed into the 9 Mt W/Mk-53 warhead deployed on the Titan II missile and the Mk-53 strategic bomb. This last version remained in active service until early 1997, making it the oldest and highest yield weapon in the U.S. stockpile. (Photo provided by Los Alamos National Laboratory Historical Department.)

Electromagnetic Pulse Preparedness – Homeland Security Challenges and DoD Opportunities

MAJ Gerald B. Popko
United States Military Academy

The threat from high-intensity, electromagnetic disturbances – commonly referred to as electromagnetic pulses (EMP) – is not new. Modern observations of naturally occurring EMPs date as far back to the so-called "Carrington Event" of 1859 when a naturally occurring coronal mass ejection (CME) induced intense terrestrial electromagnetic fields and disrupted what little electrical devices existed – telegraphs.[1] Manmade EMPs are also not new. The 1962 U.S. nuclear test known as Starfish Prime illuminated the phenomenon by unanticipatedly disrupting civilian and military electronics in Hawaii, over 1,300 kilometers away.[2] However, what has changed since these events is the ubiquity of civilian and government dependence on electronics. To this end, the U.S. military has assessed the threat of EMP effects against military targets for several decades.[3] Overlooked in this analysis is the U.S. military's increasing dependance on civilian infrastructure which presents new EMP related homeland security challenges. Therefore, while an EMP poses a clear homeland security threat, it is in the interest of the Department of Defense (DoD) to promote homeland EMP resiliency to preserve its own strategic readiness. Put another way, a domestic EMP event presents an imminent homeland security threat whose second and third order effects may compromise the DoD's ability to execute national defense at home and abroad.

Background

Though all nuclear weapon detonations produce EMPs, security researchers largely classify a high-altitude nuclear detonation, also called a high-altitude EMP (HEMP), as the most pervasive means to weaponize an EMP.[4] EMP effects are mostly line-of-sight; therefore, as a nuclear weapon's detonation altitude increases above the earth's surface, so too does the ground footprint of EMP effects.[5] Correspondingly, a nuclear detonation with an approximate 500 kilometer height of burst (HOB) could propagate effects across the entire continental United States, albeit, the energy of the electromagnetic field still decays exponentially with its propagation distance.[6] Similarly, a HEMP's high-altitude burst mitigates the casualty producing effects of the nuclear weapon (blast, thermal, and ionizing radiation) reaching the earth's surface, which largely isolates the EMP effects of the weapon. However, security researchers are also pointing to a possibility of alternative EMP weaponization via conventional explosives or microwave emitters.[7] Therefore,

MAJ Gerald Popko is an instructor in the Department of Electrical Engineering and Computer Science and a researcher in the Photonics Research Center at the United State Military Academy at West Point, NY. He has a B.S. in Physics from the Virginia Military Institute and a M.S. in Electrical and Computer Engineering from the Georgia Institute of Technology. He was previously assigned as a Fire Support Officer, Field Artillery Platoon Leader, and Battery Executive Officer in the 10th Mountain Division and an Intelligence Officer in the 3rd Infantry Division. His email address is gerald.popko@westpoint.edu.

while possible ballistic missile-delivered EMP threats by China, Russia, North Korea, and Iran may be dissuaded by nuclear deterrence strategy, a directed energy EMP strike may be seen as an increasingly viable alternative to a nuclear weapon.[8]

Alternatively, CMEs are sources for natural geomagnetic disturbances (GMD) that also produce EMP effects. While scientists generally categorize GMD-induced EMPs as potentially less destructive than HEMPs, CMEs are effectively unavoidable, with the question rather being 'when and how strong?'[9] Electricity-era society has witnessed many GMDs, with notable events occurring in 1859, 1921, and more recently in 1989 which left over 6 million customers without electricity in North America.[10]

In either case (man-made or natural), EMP's primarily affect electrical devices by coupling potentially destructive electromagnetic field energy into circuits, which may damage or destroy components incapable of contending with the induced currents. EMPs particularly affect long-line power distribution, but can also destroy sensitive electronics such as computers, telecommunications equipment, and Supervisory Control and Data Acquisition (SCADA) systems, among others.[11] The impact to electronics is typically sustained within minutes, if not near instantaneous to the onset of an EMP.[12] While the impact to electrical devices is quick, the second and third order consequences of widespread electronic failure on the economy, basic necessities, and healthcare give rise to long-term casualty estimates as high as nine out of ten Americans dead in the years following a serious EMP event.[13] As a result, while EMP events present imminent security threats, their prolonged impact present long term strategic challenges for homeland security.

Homeland Security Challenges

In the United States, an EMP event uniquely challenges the DoD and its partners across the spectrum of homeland security operations. Considering the similarities in delivery of an intercontinental surface strike nuclear weapon and a HEMP, the DoD's homeland defense mission of missile warning is largely similar. However, because effective HEMPs do not require significant reentry, adversaries have lower technical barriers for employment when compared to surface strike missiles; missile defense warning systems have comparatively shorter warning times; and missile warning can be further challenged by the possibility of a satellite-borne delivery.[14] Following an EMP, homeland security responses also differ from surface nuclear weapon strikes. CBRN consequence management is less concentrated while the potential for widespread communications failure makes initial response difficult. Communication failures will complicate local, state, and national leadership efforts to develop the situation and coordinate a response thus straining resourcing and unity of effort. Furthermore, beyond first response, consequence management faces a protracted reconstruction period. Former White House science and technology advisor Dr. John Holdren estimated reconstruction from a significant GMD to be on the order of trillions of U.S. dollars with recovery spanning upwards of four to ten years.[15] As a result, even if critical defense infrastructure is EMP hardened, the public burden may challenge the DoD to sustain protracted Defense Support to Civil Authorities (DSCA) missions during recovery.

Likewise, while tactical military equipment may or may not be EMP hardened, the civilian infrastructure the DoD relies on is largely vulnerable.[16] The DoD's dependence on civilian infrastructure in the continental U.S. (CONUS) can be inferred by considering the DoD's reliance on the civilian power grid for nearly 99% of its electrical power.[17] Perhaps more concerning, a domestic EMP event could disrupt food distribution, transportation, water infrastructure, emergency services, fossil fuels industries, and space systems regionally or even globally.[18] While disruptions of these industries immediately impact the U.S. civilian population, the DoD is largely reliant on these industries' prosperity for strategic level logistics and maintaining force readiness.[19] As a result, widespread disruptions to basic necessities within CONUS have the potential to degrade the U.S. military's sustained readiness and their ability to conduct overseas operations, whether that be for a contingency response to an EMP strike or to carry out enduring national strategy abroad. Therefore, it is in the DoD's interest to not just consider EMP resiliency from a standpoint of preserving short-term combat power, but equally as important that the DoD support homeland security initiatives to harden civilian infrastructure to sustain strategic readiness. Nonetheless, several challenges exist that may inhibit homeland security preparedness for an EMP event.

The U.S. government's contemporary understanding of EMP vulnerabilities forms one challenge to homeland security. While the DoD and Department of Energy (DoE) have conducted EMP analyses for several decades, rapid changes in technology challenge the inference of these studies to emerging electronics and security classifications further limit the ability to share classified findings through all levels of government partners.[20] Recently, Executive Order 13865 – Coordinating National Resilience to Electromagnetic Pulses – has renewed national security focus to assess EMP vulnerabilities and attempts to achieve unity of effort with tasks to the Departments of State, Commerce, Defense, and Homeland Security to conduct vulnerability assessments.[21] However, the effectiveness of such measures remains uncertain, particularly when considering the failure of larger national legislation to effectuate EMP preparedness, such as the 2013 Secure High-Voltage Infrastructure for Electricity from Lethal Damage (SHIELD) and 2014 Grid Reliability and Infrastructure Defense (GRID) Acts which Congress did not pass into law.[22] Nonetheless, the DoD should consider how to share its current understanding with government and private partners to build national EMP resilience.

Public and private partnership pose another challenge to EMP homeland security preparedness. Up front, public-private partnerships are critical for hardening power distribution due to large private investment in the U.S. power grid.[23] Additionally, second order effects to the agriculture, financial, telecommunications, energy, and transportation industries require effective unity of effort to mitigate EMP effects beyond government regulated critical infrastructure. Therefore, while such documents like the 2017 National Security Strategy outline the importance of hardening key infrastructure to weapons of mass destruction, it also underscores the importance of preparing resilient communities that are capable of coping with disaster.[24]

DoD Opportunities

The challenges mentioned above bring unique opportunities for the DoD to support EMP homeland security preparedness prior to executing missile defense and DSCA responses. On a larger scale, the DoD has decades of research analyzing its own Command and Control (C2) systems that can be applied toward assessing vulnerabilities to SCADA and telecommunications industries.[25] But all opportunities may not require significant technical partnership. The DoD can offer unique tactical experiences to Federal Emergency Management Agency (FEMA) responders. While the National Response Framework identifies unique technical skills that the U.S. military can provide to homeland security responses, such as communications skills, the U.S. military's frequent training in degraded, "analog" environments could provide additional valuable lessons for civilian partners in homeland security conducting EMP responses without significant electronic support.[26] As a result, the DoD should not just consider large-scale, high-dollar collaboration to enable homeland security partners, but it should also consider sharing tactics, techniques, and procedures that may enable homeland security partners to operate in degraded environments.

Conclusion

EMPs pose a unique homeland security threat. Manmade EMPs hold large destructive power but may be considered of limited viability for an adversary, while natural EMP-causing events are potentially less destructive, but effectively unavoidable. In either case, the homeland security response could be protracted and wide reaching. As a result, an EMP event has the potential to challenge the nation's homeland security apparatus across the continuum of operations from missile defense to consequence management. However, the DoD must also consider its role beyond preparing itself by working with homeland security partners to harden national infrastructure and to train for operations following an EMP event. By seeking these opportunities to prepare civilian infrastructure, the DoD can mutually support its role in homeland security while also investing in preserving its readiness for defense abroad.

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A Union of Pariahs

A Downside of the NPT

Major Christopher Mihal
NNSA Albuquerque Complex

The Treaty on the Non-proliferation of Nuclear Weapons (NPT) has been a bedrock of nuclear non-proliferation efforts since its inception in 1970. However, like any international agreement, it is certainly not a perfect document, and it has led to several unforeseen consequences that have become systemic in the international scene. Initial U.S. foreign policy was driven naively with the U.S. Atoms for Peace program, which provided nuclear power technology that was then used for weapons programs despite written diplomatic assurances from recipient countries that said reactors would only be used for peaceful purposes. This in turn led to the development of the NPT to deter would-be proliferators and nascent nuclear weapons programs. The NPT prohibits signatories from the sale and transfer of material/knowledge to non-NPT states. Governments that defy this rule face robust sanctions, but this had the unexpected side effect of forcing non-NPT-compliant states to turn to one another or the black market as they cannot trade legitimately with most of the international community. Cash-strapped nations that cannot legitimately trade will instead sell black market items to generate capital. Every single nation that has developed nuclear weapons since the NPT has had some degree of outside assistance, from India's exploitation of the U.S. Atoms for Peace initiative to detonate its Smiling Buddha device in 1974[i] to the extensive aid China and Pakistan have provided to North Korea.[ii, iii] Furthermore, the presence of nuclear smuggling operations in many of the NPT-signatory countries give pariah nations extensive support in developing their weapons programs, and organized crime syndicates are on the lookout for nuclear material from failed or failing states to sell to the highest bidder.[iv]

While the NPT has had considerable success in limiting the number of nuclear powers beyond the original five – U.S., Russia, United Kingdom, France and China – the way in which the five additional nuclear nations that are not compliant with the NPT acquired nuclear weapons technology indicates significant official and unofficial covert support to their programs. The five nations that acquired nuclear weapons since the signing of the treaty are India, Pakistan, South Africa, North Korea and Israel (officially unconfirmed but widely leaked due to whistleblowing efforts of Israeli nuclear scientist Mordechai Va-

Major Christopher J. Mihal is the Executive Director at the National Nuclear Security Agency Office of Systems Engineering and Integration, NA-18, in Albuquerque, NM. He/she has a B.S. in History from the U.S. Military Academy, a M.S. in Engineering Management from the Missouri University of Science and Technology, and a M.S. Nuclear Engineering from the Air Force Institute of Technology. He is a certified Project Management Professional. He was previously assigned as an Exchange Officer with 2 Canadian Mechanized Brigade Group. His email address is Christopher.mihal@nnsa.doe.gov.

nunu).[v] It is important to note that there are two components to nuclear proliferation. The first proliferation component is the actual nuclear warhead itself, whether of a gun-type or implosion-type bomb, while the second is a delivery system for the warhead, typically in the form of a ballistic or cruise missile design. Some proliferators, such as Chinese aid to Pakistan, provided both technologies,[vi] while some focused on one or the other, such as Austrian construction of Iraq's calutron magnets for uranium enrichment.[vii] It is an unfortunate fact of the global financial system that some individuals, companies, and nations will always place monetary gain over norms imposed by international treaties.

There are many routes available for a nation seeking aid to its nuclear weapons program. Sometimes nuclear components are obtained illegally, such as South Africa's theft of German URENCO centrifuge designs.[viii] Sometimes they were the work of a single employee in a company, such as an employee of the German Leybold company who sold over 750,000 items to numerous countries including Iran, North Korea, and other would-be nuclear nations through his own personal front company[ix]. Finally, sometimes it is the entire company itself involved in corruption, such as Swiss engineering firm ABB selling nuclear technology to North Korea.[x] Complicating efforts to curb nuclear proliferation is the wide variation in laws in different countries; in the aforementioned German case involving Leybold, the individual in question could not be prosecuted on a technicality, but rather was "persuaded" to retire and close his front company with a generous severance package.

There have been three primary nation-based pariah networks involved in nuclear proliferation over the years: the AQ Khan network, based out of Pakistan, which in itself was partially an offshoot of Chinese proliferation efforts to Pakistan and elsewhere; a now-defunct French-Israeli-South African nexus; and North Korean efforts to spread nuclear weapons, both for hard currency unavailable elsewhere and to support anti-U.S. regimes in countries such as Iran.[xi, xii] A fourth unintended proliferation network, beyond the scope of this paper, was the U.S. Atoms for Peace Initiative, which provided reactors subsequently used to kick-start Indian, Iraqi, Pakistani, Israeli and South African nuclear weapons programs.[xiii] All of the nations with significant nuclear weapons programs developed them owing to perceived threats. Pakistan and India developed nuclear weapons due to fear of each other, North Korea developed their program to deter the United States in the Korean peninsula, while Israel's program, and the strategic ambiguity surrounding it, are designed to deter Arab and Iranian aggression. Iran seeks a bomb to counter Israel and deter U.S. interference in the region, and, finally, apartheid-era South Africa sought nuclear weapons as a trump card against the Soviet Union, Cuba, and the myriad African resistance movements South Africa battled in the decades-long Border War. Given no recourse to acquire these weapons from countries that are signatories to the NPT, these nations began covert programs or began to assist one another, creating some strange bedfellows indeed.

The most infamous, though not the only, nuclear proliferator is Pakistani scientist AQ Khan, who sold technology, including weapons blueprints, to Libya, Iran, North Korea, and even Pakistan's mortal enemy India.[xiv] It seems that AQ Khan's smuggling career began as a state-sanctioned project by Pakistan, but over time Khan became increasingly rogue, leading to his arrest. A raid by Mossad in 2018 revealed Iran possessed an implosion-weapon design probably linked to Khan, as well as centrifuge-assistance and instructions on casting uranium metal weapons components definitely linked to Khan.[xv] Khan's smuggling network had operatives in over 20 countries,[xvi] including the United Kingdom, Malaysia, Switzerland, India, South Africa, Sri Lanka, and Germany, among others.[xvii] Khan's network even included former unemployed and disgruntled South African scientists who may have joined Khan's network or went to work for Iran,[xviii, xix] a curious inversion given their country's previous support from Israel.[xx] While initially it seemed Khan was motivated by Islamic solidarity, in the end he placed monetary gain and personal notoriety above all else; his overtures to India likely assisted in Pakistan supporting his downfall.[xxi] Khan was linked to a seized shipment of centrifuges to Libya in 2004, and he confessed to his role in nuclear proliferation; caught red-handed, Pakistan had no choice but to arrest him.[xxii]

Prior to signing the NPT in 1992, the French gave extensive support to Israel to develop its plutonium-separation nuclear reactor at Dimona in the 1960s[xxiii] and provided the MD-600 missile, which the Israelis would convert into the Jericho missile.[xxiv] The Jericho missile was in turn provided to South Africa, where it became the basis of the RSA-1 and RSA-2 missiles, and Israel and South Africa jointly worked on the space-capable RSA-3 until pressure from the United States forced cancellation of the program.[xxv.] Although much documentation was destroyed following South Africa's dismantlement of its weapons program, accession to the NPT, and government turnover to the African National Congress (ANC), there is extensive evidence of cooperation between Israel and South Africa's nuclear weapons programs. While South Africa solely developed gun-type weapons, South Africa apparently traded several hundred tons of uranium in exchange for 30 grams of tritium, a component of more advanced thermonuclear weapons.[xxvi] This corresponds to evidence that South Africa planned to expand its nuclear arsenal size and capability to fourteen weapons, including three "boosted" weapons for use on medium range ballistic missiles,[xxvii] until it became clear the ANC would come to power in South Africa, whereupon the program was cancelled and evidence of it destroyed. The rapid nature of the dismantlement and apparent unsatisfactory nature of their termination led to an unknown number of South African nuclear scientists working for various Middle Eastern nations and possibly the Khan network.[xxviii]

The final primary proliferation regime is that of North Korea. North Korean leader Kim Jong-Un has pursued a policy known as byungjin, or "parallel development," stressing nuclear weapons and economic development.[xxix] Furthermore, the North Korean Constitution has been amended to refer to itself as haekpoyuguk, or as a nuclear state, reflecting that the decision to have a nuclear weapons program seems to be permanent.[xxx] North Korea's nuclear program benefited greatly from Japanese nuclear proliferation, with many components in North Korean reactors being traced to Japanese suppliers, most of whom did so illegally to profit despite sanctions.[xxxi] North Korean nuclear trafficking is also greatly aided by Chinese companies which, legally or illegally, provide fronts to obscure the true destination of the technology North Korea is acquiring.[xxxii] Due to crushing international sanctions, North Korea has pursued a policy of international theft, hacking, and black-market activity, including selling nuclear and ballistic missile technology worldwide. Nuclear trading provides both capital as well as nuclear components neither easily obtainable nor producible in North Korea; the latter is considered a sign of North Korean and Iranian cooperation for mutual development of their weapons programs.[xxxiii]

North Korea has proliferated nuclear technology to Myanmar,[xxxiv] Syria, and Pakistan,[xxxv] and at one point, it was the foremost ballistic missile exporter in the world, selling ballistic missiles to Iran, United Arab Emirates, Vietnam, Libya, Pakistan, Egypt, Iraq, Syria, and Yemen.[xxxvi, xxxvii, xxxviii] Unlike most other countries, North Korea is willing to sell complete ballistic missiles rather than individual components and full assembly lines for such weapons, illustrated most graphically when the North Korean freighter Kuwolsan was seized by Indian authorities carrying an entire factory assembly line for SCUD missiles destined for Libya.[xxxix] North Korea's withdrawal from the NPT and non-accession to any significant export control or nonproliferation initiative[xl] is a great danger to international order. With the demise of the Khan network and the dismantlement of the Israeli-South African nexus, North Korea is now perhaps the greatest nuclear and missile technology proliferator in the world.

For pariahs that would like to acquire nuclear weapons with even further secrecy, organized crime smuggling networks also exist, though the risk of working with such unscrupulous figures is that they may sell one thing while claiming it is another. The most famous of these incidents was in 1994 when Bosnian Serb leader Radovan Karadzic, the war criminal responsible for the Srebrenica massacre, purchased an elipton bomb powered by red mercury in the belief that such a weapon of mass destruction would tip the regional power scales in Serbia's favor. Fortunately, neither the elipton bomb nor red mercury actually exist, and Karadzic received a conventional bomb with random chemicals accompanying it instead. Karadzic paid $6 million out of a promised $60 million before realizing he had been duped.[xli] Despite this, organized crime smuggling of nuclear materials, while not as prevalent as in its heyday following the collapse of the Soviet Union in the 1990s, persists. When the Soviet Union collapsed, out-of-work nuclear scientists sold nuclear material to the highest bidder to feed their families in some instances, with the largest attempt at smuggling being almost 3 kilograms of weapons-grade uranium in the Czech Republic in 1994.[xlii]

While there is some state-level coordination with organized crime to acquire nuclear material, violent extremist organizations are even more extreme versions of international pariahs, and thus have much more often worked with black marketers, both organized crime and independent criminals, to acquire nuclear weapons because pariah states are unlikely to work with them. The Japanese Aum Shinrikyo cult, responsible for the Tokyo subway sarin gas attacks, attempted to purchase nuclear weapons from Russian intermediaries, in particular disgruntled Russian scientists, and even mined their own uranium, though abandoned their nuclear weapon aspirations in favor of chemical and biological weapons. Aum Shinrikyo sought to bring about Armageddon via WMD attacks on U.S. and Japanese bases and cities; fortunately, nuclear weapons proved too difficult for them to obtain or manufacture themselves.[xliii] In another instance, a Rand study, citing a Monterey Institute of International Studies report, identified four separate attempts by Al Qaeda to acquire nuclear material on the black market.[xliv] ISIS repeatedly attempted to acquire radioactive material, though more likely for a dirty bomb than an actual nuclear weapon. A Moldovan crime syndicate was arrested trying to sell cesium to representatives they thought were from ISIS in 2015.[xlv] Italian organized crime syndicates were caught red-handed trying to sell nuclear material smuggled from Zaire (now the Democratic Republic of the Congo) to unidentified Middle Eastern buyers in 1998, and they were known to have contacts with Portuguese and Belgian businessmen as well.[xlvi] While organized crime networks rarely acquire material suitable for nuclear weapons, the nuclear material they do sell may be used in dirty bombs or for other purposes. Vigilant international cooperation and penetration of these networks is vital to prevent any dissemination of nuclear material to radical groups such as ISIS.

What is most difficult about these proliferation networks is that, until a state's government decides it is no longer threatened or when it is replaced/overthrown, states will continue to pursue nuclear technology. South Africa and North Korea are perfect examples of countries under extreme international isolation who nevertheless developed these weapons, partially due to dedication amongst its own scientists. South Africa only relinquished its weapons when the Border War ended and it was clear that the apartheid regime's days were over; Iran only suspended its program with the signing of Joint Comprehensive Plan of Action (JCPOA) and relinquishment of sanctions, although as soon as the United States withdrew from the agreement and reimposed those sanctions, Iran begin enriching uranium once more.

Nuclear weapons are viewed as intrinsic to a regime's survival by many pariahs; indeed, North Korea has placed all its bets on nuclear weapons maintaining the Kim regime in power. The fate of Muammar Gaddafi, violently overthrown and murdered following relinquishment of his nuclear weapon aspirations, has reverberated throughout the world. Ukraine is another graphic example of this; Ukraine held one-third of the former Soviet Union's nuclear weapons following dissolution,[xlvii] but voluntarily destroyed them after signing the Budapest Memorandum on Security Assurances, whereby the United States, Russia and United Kingdom assured they would refrain from the use of force in Ukraine and provide assistance if Ukraine became the victim of an act of aggression.[xlviii] Unfortunately, these assurances haven't prevented Russia's slow dismemberment of Ukraine by occupying Crimea and invading the Donbas region; some Ukrainian politicians state this would not have happened if they had kept their nuclear weapons.[xlix] These examples may have unintentionally driven other authoritarian regimes, such as Iran, to hasten efforts to become a nuclear power. Breaking these pariah networks is difficult, but working to encourage normalization of relations with these countries can shrink the networks and close outlets for capital and nuclear technology; Myanmar's move to democracy ended its nuclear program, and similar initiatives may bear fruit otherwise. Violence tends to push isolated extremes to desire nuclear weapons more; the Israeli strike on the Osiraq reactor was cited as the primary motivation for Saddam Hussein to begin enriching uranium, for instance.[l] Providing incentives for countries to accede to treaties they have not – as South Africa did with the NPT – could lead to further arms reductions and nuclear program dismantlement. Leveraging regional powers – China and Russia in the case of North Korea, Turkey in the case of Iran, as examples – may be the best way to strike the networks from the top-down. Bottom-up strikes will require law enforcement and customs officials to be vigilant on nuclear smugglers and to monitor companies that manufacture dual-use technologies closely. Only a multifaceted, international approach will adequately counter and prevent further nuclear proliferation.

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The North Korean Nuclear Program

CDT Justus G. E. Robertson
United States Military Academy

Introduction

The Democratic People's Republic of Korea (DPRK) has not published an official nuclear doctrine to date. This article serves to provide an informal doctrine by analyzing official statements made by members of the Kim Regime (1948 -), past assessments of DPRK nuclear doctrine, and public general consensus on government organizations, nongovernment organizations, the United States, and our partner nation intelligence communities.

Background

The DPRK maintains international notoriety making use of nuclear rhetoric and actively developing a nuclear arsenal. The purpose of this aggressive behavior is founded in the desire to maintain the legitimacy of and to protect the Kim Regime from foreign threats. The origin of this perceived need for a nuclear deterrent can be considered a response to former United States President Truman's 1950 public statement admitting to considering the employment of nuclear weapons in ending the Korean War.[1] Kim Il Sung was driven to seize power and secure his regime through a strong military. This ambition later translated to his son, Kim Jong Il, who prioritized the development of nuclear capable intercontinental ballistic missiles (ICBMs) as a means of securing the regime from foreign powers. Kim Jong Il imparted his vision unto his son, ensuring generational inheritance of his nuclear agenda.

Nuclear Weapons Development

Rodong Sinmun's—the newspaper of the Central Committee of the Workers' Party of Korea (WPK)—2013 article "Making Nuclear Weapons Smaller, Lighter, More Diversified, and More Precise," outlined the lines of effort in working towards a more sophisticated nuclear program: increasing the credibility of North Korea's nuclear force and expanding options for flexible nuclear responses.[2] These objectives follow the perceived limitations preventing the regime from developing nuclear armaments and delivery systems capable of reliably delivering nuclear payloads varying in size and delivery system range. Defined prerequisite goals include miniaturization, employing lighter-weight materials, diversifying the nuclear arsenal, and increasing precision.[3]

CDT Justus Robertson is a cadet at the United States Military Academy, in West Point, NY. He was previously assigned as an intelligence analyst at the 1SFG(A) HHC All-Source Production Section with a focus on the Korean Peninsula and Nuclear related events. His email address is Justus.g.robertson.mil@mail.mil.

Miniaturization

North Korea defines miniaturization as "the manufacturing of a nuclear weapon with explosive power under 15 kilotons."[4] The emphasis on developing smaller nuclear warheads would equip the DPRK with the capacity to make its array of delivery systems nuclear-capable. This broadens North Korea's nuclear and missile programs by optimizing the nuclear yield of their warheads. This permits the nuclearization of smaller missile systems, and production of warheads requiring less fissile material—increasing the efficacy of DPRK nuclear development, as more warheads could be produced per year. Development of these smaller warheads also enables the DPRK to conduct scalable nuclear responses—smaller yield detonations on target and the establishment of more economical nuclear weapons production.

Reducing Weight of Nuclear Weapons

North Korea believes that the weight of its delivery systems is hindering their capability to travel longer distances. To solve this problem, it actively conducts research on viable alternatives to current constructive materials to develop capacity to range additional countries.[5]

Diversification of Missile Systems

The DPRK guides its weapons development with an aim towards "[t]he manufacturing of various types of nuclear weapons with the aim of successful attainment of a wide range of military objectives."[6] The means by which North Korea classifies nuclear weapons are by the nuclear core reaction, power and range, and target detonation altitude. The thorough classification process demonstrates the sophistication the nuclear program is aspired to achieve. Categorizing missile systems by range suggests that the DPRK are seeking to develop their shorter-range missile systems alongside their long-range systems. North Korea has demonstrated varied physical structures of missiles, which in the absence of concrete specifications, suggests an array of potential capabilities. One such variation to the physical construction of their delivery systems is in the reentry vehicle of the KN-22 ICBM, which had a blunted nose compared to the pointed tip seen in previously developed delivery systems.[7] This change could suggest the implementation of alternate payloads, larger payloads,[8] and more likely, a forward-seated payload, which would increase stability during reentry. The DPRK's demonstrated alterations to their delivery systems is representative of an increasingly sophisticated missile program, which precedes and suggests equal sophistication of the DPRK nuclear program. North Korean implementation of solid and liquid propellants and different flight control mechanisms (jet vanes, gimbaled thrust, etc.) demonstrate a focus on variable testing conducive to continued growth both in range and accuracy of their delivery systems.

Propulsion

DPRK maintains facilities capable of domestically manufacturing both liquid and solid propellants for use in their delivery systems.[9, 10] The use of less-sophisticated propellants suggests that North Korea has not researched and developed the facilities necessary to reliably store and transport more efficient (and volatile) propellants. The development of which would increase the reach of each DPRK missile system by increasing the burn rate[11] of propellants used, maintaining thrust for a greater duration.

Current Nuclear Inventory Assessment

In January of 2019, analysts at Rand Corporation created projections for the DPRK's nuclear inventory in 2020. They assessed that North Korea could possess between 30

– 100 nuclear weapons.[12] These assessed values hinge upon the belief that the DPRK possessed between 15 – 60 nuclear weapons at the time of publishing. The National Committee on North Korea assessed in April of 2018 that the DPRK possessed enough plutonium to produce 5 to 17 warheads.[13] Due to the DPRK's secretive nature regarding its nuclear program, these predictions are speculative and for that reason vary significantly. The above assessments were taken at different times, at different stages of nuclear development, and used different criteria to project future warhead inventory sizes. The assessment provided by Rand Corporation is more than likely the most accurate prediction of the size of the current DPRK nuclear inventory as this assessment was conducted on a more developed DPRK nuclear program and predicts total inventory a small period of time from the time of assessment. Additional factors affecting the DPRK's possible rate of production of nuclear warheads are the conversion of civil nuclear enrichment facilities, the amount of fissile material expended per test detonation,[14] and the size of nuclear warheads being produced.

Resiliency of Counterstrike Capability

The DRPK likely relies on the capability to rapidly relocate, stage, and fire their longer-range delivery systems to provide the capability to evade and respond to incoming nuclear threats. The need for this capability stems from the DPRK's reliance on their nuclear program to deter foreign aggression, as any losses of nuclear arms through foreign sabotage or proactive destruction would result in a weaker ability to protect the Kim Regime. The DPRK centers its nuclear employment strategy around assurance of a secure second-strike capability, ensuring that the DPRK remains nuclear capable following nuclear strike(s) against its homeland. The current means of protecting nuclear weapons is by storing them in underground facilities (UGFs) to protect them from such strikes and to prevent detection and definitive identification of the size of the DPRK nuclear arsenal. It also employs transporter erector launchers (TELs) to relocate and fire from varying locations, the use of camouflage sites to covertly stage and store nuclear weapons, and aboveground delivery systems.[15] The entire DPRK missile arsenal is capable of being outfitted to a TEL or transported by multiple support vehicles for staging at several established launch locations. The focus on missile mobility instead of the missile launch facilities maintained by larger countries reflects the reliance on the nuclear arsenal for protection.

Nuclear Use Scenarios

Historically, KJU's official statements and their timing suggest that the DPRK would currently use their nuclear arsenal only in the event of a ground invasion of North Korea or a regime collapse. KJU has threatened to use nuclear weapons as a means of lifting sanctions emplaced on the regime and to deter perceived threats in the form of redistribution of foreign forces towards the DPRK border or the conduct of military exercises in proximity to the DPRK (ROK or DPRK economic zones). The DPRK has threatened nuclear action and hinted at willingness to take nuclear action in response to many issues,[16, 17] suggesting that the DPRK relies heavily on virtual deterrence, in which the ambiguity of the conditions under which the DPRK would actually use nuclear weapons provides additional security,[18] the absence of an official nuclear doctrine further reinforces this form of deterrence. The viable use scenarios are tightly constrained as the DPRK, a growth-oriented country, cannot yet afford to draw excessive notoriety beyond what is captured by their already hostile rhetoric. Engaging in unnecessary combat or instigating further sanctions would impede rapid growth of their nuclear program. Although these sanctions have not been largely effective—as the continued development of the DPRK nuclear program would indicate, they do reduce the availability of materials needed and are a tradeoff the Kim regime must accept when issuing hostile rhetoric or taking hostile actions. The below nuclear use scenarios are that author's assessed responses (based on open-source analysis) to a ground invasion of North Korea.

<u>Reactive Launch</u>

In the event of a ground invasion aimed at unseating the Kim regime from power, KJU would likely conduct measured nuclear strikes, miniaturized warheads with smaller yields, against invading forces while threatening countervalue (significant non-military targets, most likely densely populated cities) strikes to deter further advance into North Korea. Threatening launches on countervalue targets produces a significant moral dilemma to the aggressing nation(s) as further aggressive actions will incur multiple mass casualty incidents, the second-order effects of which would likely be mass civil unrest within the affected countries with the intent of compelling the invading countries to withdraw forces from the peninsula. If this moral dilemma does not deter a continued invasion and a sizeable threat to the regime is expected—likely due to hostile encroachment on Pyongyang, the DPRK would likely offer a final ultimatum or bargain. If this fails to diffuse the situation the DPRK would likely launch all postured missiles at a combination of countervalue and counterforce (military targets, likely centers of command and control and storage facilities) targets. By expending all nuclear munitions, KJU would ensure invaders or their allies incur maximum losses at home and abroad while denying seizure of DPRK nuclear weapons. This course of action is supported by the precedent established by past escalation of nuclear testing and hostile rhetoric during operations Key-Resolve and Foal-Eagle.[19] This response is a product of the DPRK's belief that the drill is conducted in preparation for an invasion of North Korea.[20, 21]

Rand Corporation assesses that, in the event of a salvo launch, roughly half of nuclear launches conducted would be aimed at counterforce targets, while the remainder would be reserved to threaten countervalue strikes "against cities in South Korea, Japan, China, Russia, and—if they develop the delivery means—targets in the United States."[22]

<u>Defensive Detonations</u>

Alternately, the DPRK could relocate nuclear warheads currently stored in UGFs south towards the DMZ for remote, on-site detonation. The prerequisites for this nuclear use scenario are the DPRK not possessing the capability to rapidly expend all nuclear munitions or the DPRK lacking means of reliably ranging intercontinental targets. A regime assessment that the Terminal High Altitude Air Defense (THAAD) battery emplaced in South Korea or any additional air defense systems emplaced in other overflight countries will intercept a missile mid-flight could be a compelling reason to decide against missile launch and rather on-site detonation. Research conducted by the United States Department of Health & Human Services assesses that INDs are capable of producing pockets of radiation for extended periods.[23] INDs are less sophisticated than missile warheads by nature and the DPRK—possessing a growing nuclear program for over ten years, should be more than capable of matching or exceeding the area denial capabilities of INDs. KJU could prevent and deter a continued invasion by adopting a nuclear denial strategy: degrading the aggressing force's rate of march through North Korea while purchasing the time necessary for the DPRK to bargain and negotiate a truce to preserve the regime. Additionally, shorter-range nuclear missile systems could be launched at targets within North Korea to establish contaminated areas as necessary to further delay friendly force flow within the Korean Peninsula. This scenario hinges on the assessment that KJU is willing to incur losses caused by detonations and mass displacement of North Koreans resulting from the emplacement of nuclear weapons to preserve the Kim regime.

Nuclear Proliferation Risk Factors

The DPRK has lost the majority of its official trade relationships due to United Nations sanctions. Resulting sanctions emplaced by partner nations have left the DPRK with few partners for missile component sales. The DPRK's remaining endeavor is collaborative missile development with Iran and Syria.[24] Pyongyang's need for capital to continue to research and produce nuclear warheads and delivery systems coupled with the precedent of parallel missile developments between Iran and North Korea suggests a willingness to sell developed nuclear technologies to Iran.[25] North Korea has also been contracted by Syria to construct a nuclear reactor, establishing precedent for sharing nuclear technology with other nations.[26] North Korea poses a significant threat to proliferate nuclear research as they possess two viable markets through which to proliferate. The DPRK is unlikely to sell any weapons from its prized nuclear program but would likely sell nuclear and missile technologies to continue funding nuclear research and development. Proliferation would frustrate nonproliferation and counterproliferation efforts made by the United Nations, further destabilizing the global nuclear environment and potentially affording North Korea distraction from their nuclear development efforts.

In the event of a regime collapse, there is a significant risk of nuclear proliferation. Nuclear scientists would likely flee persecution or seek employment within other nations, bringing with them all nuclear research. This is especially injurious should the scientists travel to countries that have not yet developed nuclear capabilities. The arrival of the DPRK scientists would establish the receiving countries as viable nuclear threats as they now have individuals capable of reproducing nuclear weapons provided the receiving states could produce the materials needed.

Additionally, the absence of a designated successor outside of the Kim family would create a power vacuum, during which influential military officials and advisors to the late Supreme Leader would engage in the ensuing power struggle. During this time, the North Korean population—lacking any official leadership and aggravated by their now war-torn country and displacement from their homes would likely start riots throughout the country. The chaos created both in the government and civil sectors creates a real risk for the acquisition of nuclear weapons by non-state actors or government officials seeking to impose their will over their competition, creating a more volatile nuclear environment.

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Reconciling Conflicting Estimates of the Beirut Explosion Yield and Mushroom Cloud Height: Effects of an Aqueous Near Source Environment

Peter Goldstein
National Atmospheric Release Advisory Center (NARAC)
Lawrence Livermore National Laboratory (LLNL)

Summary

Initial estimates for the explosive yield of the August 4, 2020 Beirut explosion varied widely and, in some cases, were inconsistent with what would be expected based on the amount of ammonium nitrate reportedly stored at the Beirut harbor. Furthermore, initial estimates for crater size, seismic magnitude, and mushroom cloud height also seemed to be in conflict with one another and the reported amount of ammonium nitrate. In this article, I describe my efforts to understand and reconcile these discrepancies by taking the near source environment into account.

I use crater dimensions to estimate the yield of the August 4th, 2020 Beirut explosion to be equivalent to approximately 1.4 kilotons of TNT with a lower bound of about 0.7 kilotons. Based on the mass of ammonium nitrate reported to have been stored at the Beirut harbor, I assume an upper bound for the yield of 2.75 kilotons. However, it is highly likely that the yield was less than 2.75 kilotons, since reported values of TNT equivalent mass of ammonium nitrate explosions are typically much less than one hundred percent of the mass of the explosive. The crater-size based yield estimates are based on crater radius estimates from satellite imagery and empirical curves and data for scaled crater radius from past chemical and nuclear explosions. I present evidence that suggests that the relatively large crater radius is due to a high degree of coupling of shock wave energy to the surrounding medium and a reduction of the effective stress because of a high level of saturation of the geologic media beneath the explosion. I provide yield estimates based on seismic body-wave magnitude and crater depth as corroborating evidence.

I compare preliminary estimates for the maximum debris cloud height, based on cell phone videos/images, with predicted maximum heights for this yield range from empirical formulas and numerical cloud-rise models. Based on a preliminary analysis of cell phone footage, the observed maximum cloud height is estimated to be approximately 1600 m.

Peter Goldstein, Ph.D. is a Physicist at the National Atmospheric Release Advisory Center (NARAC) at the Lawrence Livermore National Laboratory (LLNL), in Livermore, California. His current work focusses on the development of capabilities for modeling atmospheric dispersion of hazardous materials and radioactive fallout. He has prior experience with explosions while working in the fields of seismology and shock wave physics. He has a B.S. in Physics from the University of Massachusetts and a Ph.D. in Physics from University of California at Santa Barbara. Prior to joining LLNL he spent one year as a National Research Council Fellow at the United States Geological Survey in Menlo Park, California. His email address is goldstein1@llnl.gov.

This is much lower than that predicted using standard empirical formulas and buoyant cloud rise models.

I present results from a modified buoyant cloud rise model that more accurately predicts the maximum cloud height by allowing for the inclusion of a fixed amount of air and/or water into the fireball at the start of cloud rise. The amount of air or water that needs to be added at the start of the explosion, to reproduce the observed maximum cloud height, is relatively small compared to the total mass of air expected to be entrained during cloud rise. A much greater amount of dry air or debris is required, relative to water, for an equivalent reduction in maximum cloud height. The ammonium nitrate is one possible source for water in the fireball since it was being stored in a very humid environment and ammonium nitrate is known to be hygroscopic. The ground beneath the explosion, especially if it were saturated, and the nearby harbor could also have been sources for water or debris in the fireball.

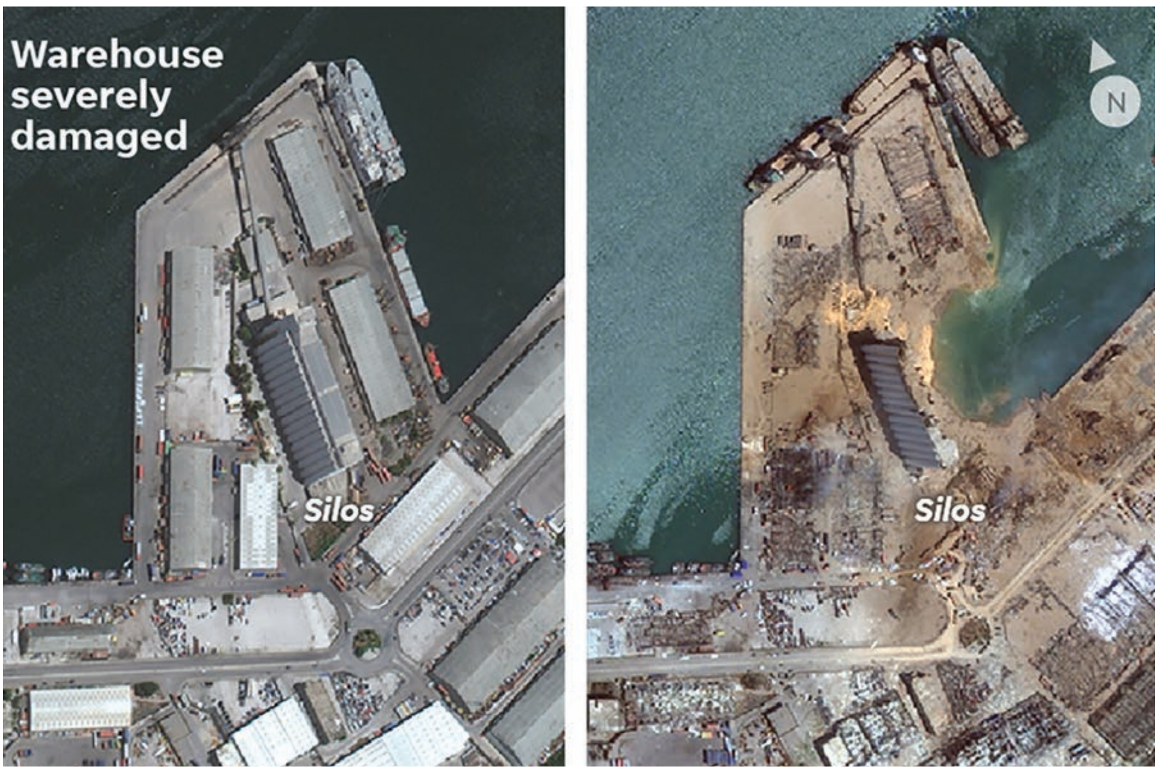

Figure 1. Before (left) and after (right) image of the crater caused by the August 4th, 2020 Beirut explosion (USA Today, August 6th, 2020).

Introduction

The development of accurate models for predicting effects of large explosions requires an understanding of the relationship between the explosive yield and effects like crater size, blast wave damage, seismic observations, and the amount of cloud rise. This is also important for the development of accurate models of the hazard from the transport of debris to surrounding areas. Confidence in the reliability of such models is critical for emergency response planning to mitigate potential consequences from accidents such as the Beirut explosion or deliberate acts that could involve improvised nuclear devices or radioactive dispersal devices.

Extensive work has been done on the relationship between crater dimensions and explosive yield and much of that work can be found in the impact and explosion cratering literature (e.g., Roddy et al., 1977). Prior work on the relationship of cloud rise to explosive yield is also extensive. Much of the early work related to nuclear explosion yield, crater radii and cloud rise can be found in Glasstone and Dolan (1977). Recent work by Spriggs et al., (2019, 2020) is increasing our understanding of these phenomenology substantially.

Observations of the August 4th, 2020 explosion at the Beirut harbor provide a unique opportunity to investigate such models. For example, Diaz (2021) used Taylor's method (1950) and observations of the Beirut explosion fireball radius as a function of time to estimate a yield for the Beirut blast of approximately one-kiloton. A similar preliminary analysis by Rigby et al., (2020) used empirical fireball radius vs time curves of Kingery and Bulmash (1984) to estimate a yield of 0.5 kiloton with an upper bound of 1.1 kilotons. These estimates overlap with, but are a bit lower than those found in this paper. However, these estimates do not account for potential effects that water entrainment and the high relative humidity in the Beirut harbor could have had on the shock wave. This paper provides some evidence that suggests that there may have been significant water entrained in the fireball and that this entrainment led to weaker cloud rise and presumably a weaker shock wave. Furthermore, work by Huang et al., (2008), and many of the references they cite, suggest that the high humidity in Beirut would also have weakened the shock front and reduced the shock wave speed. At fifty percent humidity Huang et al. see reductions in peak shock wave speed on the order of ten or more percent, and the humidity in Beirut is significantly higher than fifty percent. The implication is that these arrival-time based methods could significantly underestimate the yield. Additional work to predict the effects of water entrainment and/or humidity on the shock wave strength and arrival-time seem warranted but are beyond the scope of this paper.

In this paper, I investigate the relationship between yield, crater size, seismic magnitude, and cloud rise and reconcile what initially appeared to be discrepancies between these observations and various estimates for the yield.

Yield estimate based on prior scaled crater radius data

Estimates of the crater diameter of the Beirut explosion have been obtained from Satellite imagery and values are provided in multiple news media reports (e.g., Figure 1) with typical values ranging between 120 m and 140 m (radius between 60 m and 70 m). Using this crater radius range and prior explosion scaled crater radius measurements as a function of depth in wet and dry media (Figures 2 and 3), I estimate a yield of 1.4 kilotons with a range between 0.7 and 2.75 kilotons of TNT (Table 1).

I use a yield value based on the scaled crater radius in wet media (1.4 kilotons) as my preferred yield because it seems likely that the media below the explosion was highly saturated due to its proximity to the harbor. Furthermore, the yield range based on previous estimates of chemical explosion scaled crater-radius values in dry media are well above the likely maximum yield of 2.75 kilotons which is based on the reported amount of ammonium nitrate stored at the Beirut harbor, 2750 tons, and a TNT equivalence of 100% (Table 1).

Table 1. Yield estimate based on crater radius in wet and dry media				
	Observed Radius (m)	Chemical Explosion Scaled Radius (m/kt$^{1/3.4}$)	TNT Equivalent Yield(kt)	TNT equivalent Yield/2.75
Preferred yield - Y(kt)	**65**	**59.5**	**1.4**	**0.49**
Wet soil lower bound	60	68	0.7	0.24
Upper bound from amount of ammonium nitrate assuming 100% TNT equivalence			2.75	1.00
Wet soil upper bound	70	42.5	5.5	1.98
Best dry soil value	65	35	8.2	2.98
Dry soil lower bound	60	40	4.0	1.44
Dry soil upper bound	70	25	33.1	12.05
Dry to wet media crater radius scale factor			1.7	

Table 1. Beirut explosion crater-size and yield. The ratio of the yield to 2.75 kilotons of TNT is given in the far-right column.

In this section, I explain how I estimated the scaled crater radius for a large surface chemical explosion over wet soil. Unfortunately, there is limited if any data for such explosions. As an alternative, I used scaled crater-radius data for chemical explosions in dry media (Nordyke and Williamson, 1965, Figure 2), and estimates for the relationships between scaled crater-radii in wet and dry media based on observations of nuclear explosion in wet and dry media in Nordyke (1977) and Patteson (1960), Figure 3.

Figure 2 shows the apparent crater radius from several chemical and nuclear explosions in dry alluvium. These data suggest that a surface chemical explosion in dry alluvium would produce a scaled crater radius of roughly 35m/kt$^{1/3.4}$ and that the range would likely be between about 25 m/kt$^{1/3.4}$ and 40 m/kt$^{1/3.4}$.

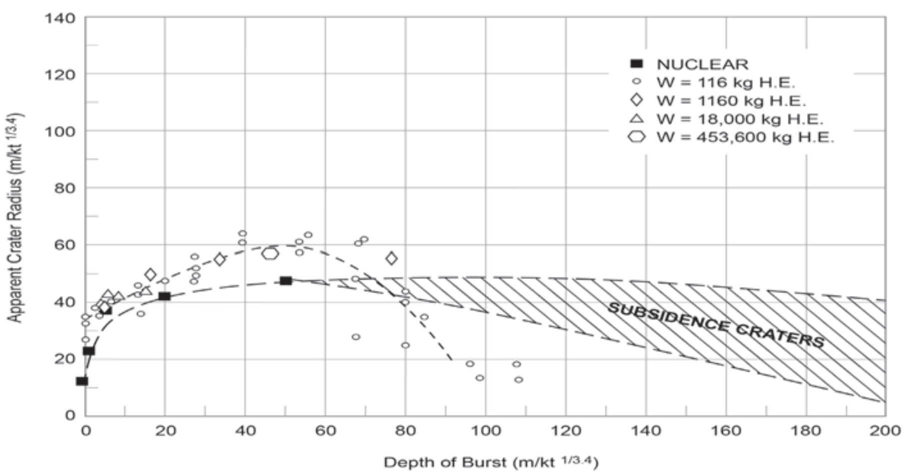

Figure 2. Scaled crater radius vs depth of burst in dry media. The scaled radius for a chemical surface burst (y-axis intercept of dashed curve) is approximately 35 m/kt$^{1/3.4}$ with scatter in the data suggesting an approximate range between 25 and 40 m/kt$^{1/3.4}$ (Nordyke and Williamson, 1965).

Figure 3 (Nordyke, 1977, Patteson, 1960) includes additional data on crater radius vs yield from explosions in or near highly saturated media. This data and many of the observations in Nordyke (1977) and Patteson (1960) suggest that an explosion in saturated media is likely to produce a much larger crater. Based on these data, Patteson suggests that, on average, the scaled crater radius of explosions in wet soil are approximately 1.5 times those in dry soil. The surface explosion scaled crater radius values on the right-hand-side in Figure 3 suggest a wet-to-dry, scaled crater radius ratio of about 1.7 with a lower bound of about 1.5. The data also suggest an upper bound of about 2.0, but that value is based on very large, megaton explosions where the crater boundary was much more difficult to determine and was often affected by phenomena that aren't present at the sub-100 kiloton range that we are interested in (Patteson, 1960). I use a ratio of the surface values from the Patteson's (1960) curves, 1.7, to calculate the preferred yield, 1.4, and lower bound, 0.7, in Table 1. Switching to Patteson's average value of 1.5 would change my preferred yield and lower bound to 2.1 and 1.0 kilotons, respectively. Using an upper bound for the wet-to-dry scaled crater radius ratio of 2.0 would change the preferred yield and lower bound to 0.8 and 0.4 kilotons, respectively. However, this larger scaling factor is based on megaton explosions and probably does not apply here.

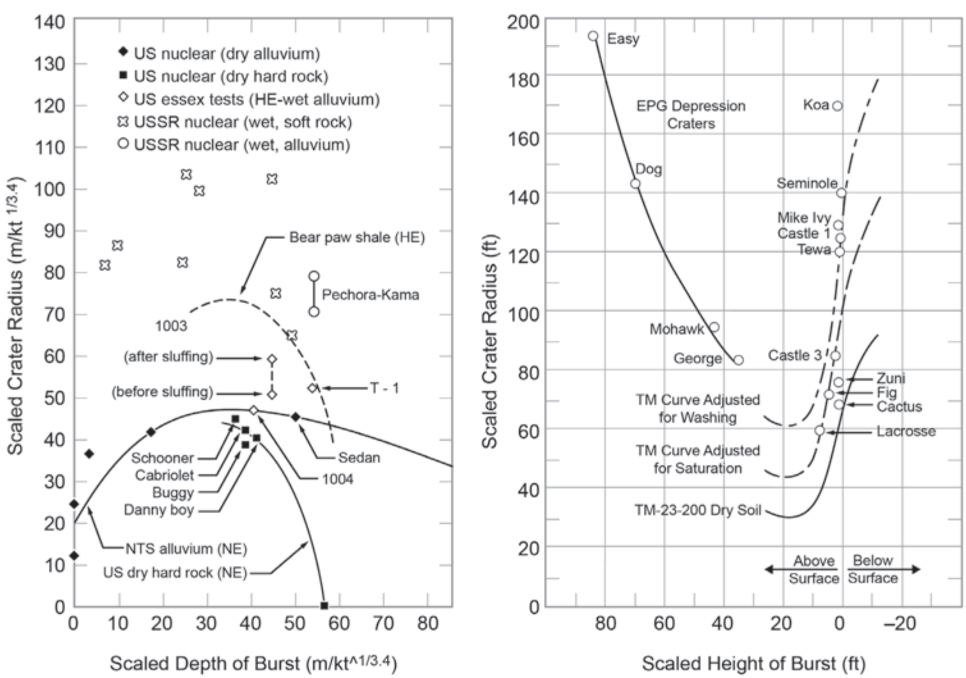

Figure 3. Scaled crater radius vs depth of burst in wet and dry media. At the surface, the wet media crater radii are roughly a factor of 1.7 times those for dry media (Nordyke, 1977, Patteson, 1960).

When estimating the yield, I also account for the uncertainties in the observed crater diameter shown in Figure 1. The primary uncertainty is caused by its elliptical shape. I use typically reported values (120 to 140 m) for the crater diameter range and use the midpoint of these values as the preferred estimate. Estimates for the yield and its range, based on these values and the above values for scaled crater radius, are provided in Table 1.

Yield estimate based on prior scaled crater depth data

There is limited and conflicting information on the depth of the Beirut explosion crater. Dadouch (2020) reports a crater depth of about 15 yds (14 m) and multiple sources report a depth of 43 m (Wikipedia, 2020). Dadouch's (2020) value is probably the more accurate one since the larger depth, 43 m, would imply a very large yield (approximately 47 kilotons) based on the prior crater-depth scaling data. The larger value probably should have been reported as feet rather than meters. If so, both values would be very similar.

Unfortunately, scaled crater-depth data from large chemical explosion is also limited, and as indicated by Nordyke (1977), highly variable. Data from nuclear explosions in Patteson (1960) appear to be more reliable (Figure 4).

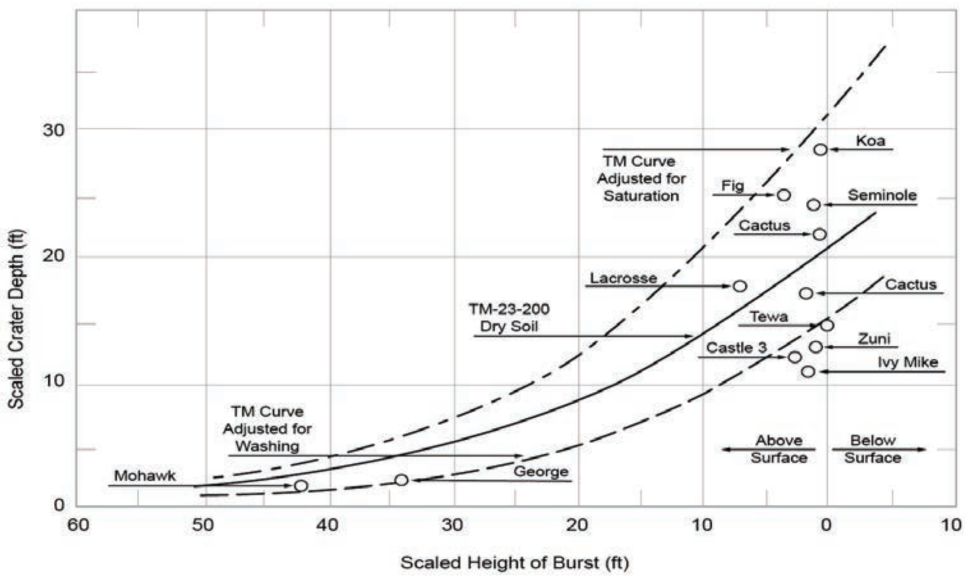

Figure 4. Scaled crater depth vs height of burst in wet and dry media (Patteson, 1960). The intercept of the dry and saturated media curves with the vertical axis at a height of burst of zero (surface burst) are given in meters in Table 2.

Excluding the very large nuclear tests, these data suggest scaled crater-depths ranging from 6.4 to 9.4 m/kt $^{1/3}$ with the larger value applying to explosions in wet soils. I use these values to estimate an equivalent nuclear yield and apply a scale factor based on observations by Glenn and Goldstein (1994) and Goldstein and Jarpe (1994) to convert them to equivalent chemical explosion yields (Table 2).

Table 2. Yield estimates based on crater depth.					
	Observed depth (m)	Nuclear Explosion Scaled Depth (m/kt$^{1/3.4}$)	Equivalent Nuclear Yield (kt)	TNT Equivalent Yield (kt)	TNT Equivalent Yield/2.75 kt
Wet soil	14.0	9.4	3.3	1.6	0.6
Dry Soil	14.0	6.4	10.5	5.2	1.9
Chemical/nuclear explosion yield scale factor (Glenn and Goldstein, 1994; Goldstein and Jarpe, 1994)			2.0		
Yield scaling exponent			3.0		

Table 2. Beirut explosion crater-depth and yield. The adjustment to correct for differences in chemical and nuclear explosion scaled crater depths is explained in the text. The ratio of the chemical explosion yield to 2.75 kilotons of TNT is given in the far-right column.

Crater-size yield estimate summary

In the remainder of this paper, I use the yield based on the crater radius as my preferred yield. I provide additional estimates of yield from crater depth measurements and seismic magnitude estimates for comparison but prefer the crater radius-based estimate because I believe the Beirut explosions crater diameter measurements and scaled radius estimates are reliable and lead to yield estimates with less uncertainty than the other methods. My preferred estimate for the yield, 1.4 kiloton, is about 49% of what would be expected from 2.75 kilotons of TNT (Table 1). This value for TNT equivalence is consistent with the range of typical values cited for ammonium nitrate (e.g., Torok and Ozunu 2015).

There are many factors that could have affected the yield estimate. For example, it is likely that the ammonium nitrate absorbed a significant amount of water while it was stored for seven years in the high humidity environment of Beirut harbor (typical August humidity of 66% - https://weather-and-climate.com/average-monthly-Humidity-perc,Beirut,Lebanon). It also seems likely that there were other energetic materials in the vicinity of the ammonium nitrate. In fact, many small fireworks-like explosions were seen in videos of the event (Gambrell and Federman, AP news, August 5, 2020, https://apnews.com/article/israel-ap-top-news-international-news-middle-east-lebanon-cbeb3263d-6fc30a63a0300f588e7207b) prior to the main blast. As suggested earlier, the medium beneath the explosion could have been highly saturated and many other structural and geologic features could have affected the explosion. Nordyke (1977) describes examples where sharp transition from soft alluvial layers to hard rock layers can have significant effects on crater dimensions. Such transitions can trap energy in the surface layers and direct it laterally enhancing crater formation. Such features also could have contributed to the elliptical nature of the crater. Additional information on the underlying geology and more sophisticated modeling (e.g., Morris et al, 2020, 2021) is needed to evaluate this possibility.

The configuration of the explosives and the confinement of the explosion by its surroundings may have also played a role in crater formation. The consistency between the shape and orientation of the visible crater rim and the warehouse the explosive was stored in prior to detonation provides some evidence that the explosion configuration and surrounding man-made or geologic structures may have played some role. The lack of crater boundary on the harbor side of the crater is evidence of this. However, the lack of significant asymmetry in the direction perpendicular to the harbor suggests the influence of the harbor was probably small.

Constraints on the yield from seismic body wave magnitudes

Seismic magnitudes are another measure that is frequently used to estimate explosion yields and significant work has been done to develop magnitude-yield relationships for explosions (e.g., Mueller and Murphy, 1971). However, there is a high degree of uncertainty associated with chemical explosion magnitude-yield relationships due to a variety of factors including variations in near-source and near-receiver geologies, and the explosion emplacement conditions including the depth of the explosive, its spatial distribution, its firing sequence, and the level of media saturation (e.g., Khalturin et al., 1996).

Estimating yield for large chemical explosions is particularly challenging because they occur relatively infrequently and, as in the case of the Beirut explosion, their yields can be affected by a variety of factors including emplacement conditions and firing sequence. However, methods for estimating magnitude and its limitations are well documented and understood. Furthermore, there are readily available magnitude estimates for the Beirut explosion from reliable sources (e.g., the U.S. Geological Survey, USGS, mb=3.3, the German Research Centre for Geosciences, GFZ, mb=3.5, and the UC Berkeley Seismology Laboratory, mb=3.4). These magnitudes provide an additional observation that can be used to compare with my crater-size based yield estimates.

My seismic yield estimate is based on prior observations from nuclear explosions that caused cratering. I account for the well documented systematic difference in the magnitudes expected from chemical and nuclear explosions (e.g., Glenn and Goldstein, 1994 and Goldstein and Jarpe, 1994). Large, spatially localized chemical explosions have been shown to generate seismic signals that are roughly a factor of two greater than those from a similar yield nuclear explosion. These differences are largely due to the significant amount of nuclear explosion energy that goes into radiation.

For magnitude, I use the median of three estimates from the USGS (mb=3.3), Germany's GFZ (mb=3.5), and the Berkeley seismological laboratory (mb=3.4) because these organizations routinely estimate magnitudes from many events and their estimates are considered to be reliable by the seismic community.

In the following, I compare the median seismic body-wave magnitude estimate with values found for prior nuclear explosions that caused cratering (Rodean, 1970). My analysis of these measurements and their relationship to the yield is not intended to be precise since there are many factors that introduce significant uncertainties. My primary interest is to see if a seismic magnitude-based estimate is consistent with the crater-size based yield estimates.

A modified version of Rodean's data is shown in Figure 5. I focus my attention on the data for explosions in alluvium and have drawn a line through the data to approximate the overall trend. I have ignored the data points for the Sedan, Fisher and Haymaker explosions because these explosions were buried at significant depths compared to near surface detonations. I have placed a red circle at the estimated magnitude, 3.4, on the trend line and added a horizontal line corresponding to a magnitude of 3.4 and a vertical line through the Beirut explosion to facilitate reading the corresponding equivalent nuclear yield.

The equivalent nuclear yield is a little less than 4 kilotons. After correcting for the difference between chemical and nuclear explosions (Glenn and Goldstein, 1994, Goldstein and Jarpe, 1994) the body-wave magnitude suggests a chemical explosion yield of roughly 2 kilotons. Given that uncertainties in Seismic yield estimates are likely to be at least a factor of two (Khalturin et al., 1996), this result is consistent with those obtained using the crater-size measurements.

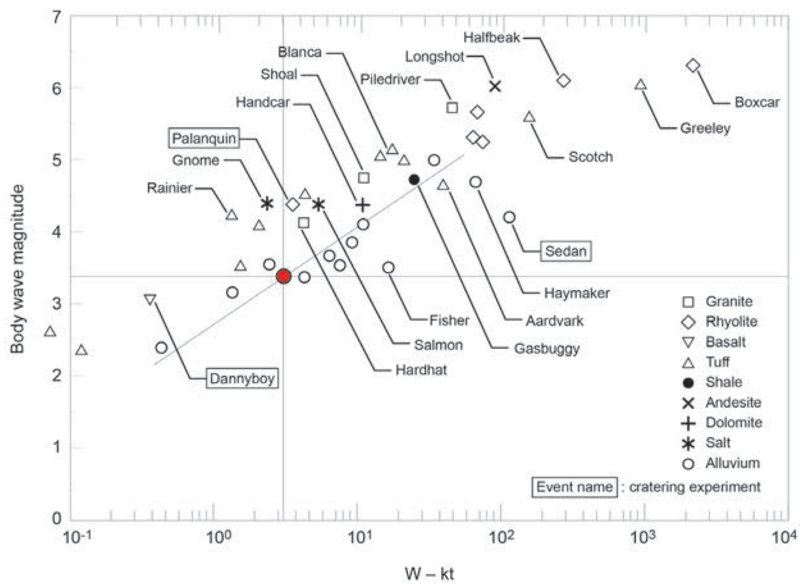

Figure 5. Seismic magnitude vs yield for nuclear explosions that caused cratering and the Beirut explosion. The Beirut explosion is shown as a red circle. The inferred nuclear yield would be approximately 4 kt. The equivalent chemical yield is about 2 kt.

Constraints on the potential amount of debris entrainment using crater size

This section uses crater size to provide a rough estimate of the upper bound for crater mass that could be entrained by the Beirut explosion debris cloud. In subsequent sections I focus on the effect that this entrainment could have on the debris cloud height.

I treat the crater as the lower half of an ellipsoid with a volume:

$$V = 4\pi * R_a * R_b * R_c / 6$$

Where Ra, Rb, and Rc are the radii of the ellipsoid along its three axes. Using the previously stated bounds on the crater radius (120 and 140 m) and a depth of 14 m (Dadouch, Washington Post, August 11th, 2020) the crater volume is roughly $5×10^5$ m^3. If we assume an average density of 2500 kg/m^3, (Manger, 1963) the total crater mass is about $1.25×10^9$ kg. This suggests that crater debris could account for a significant amount of any entrained mass.

In highly saturated media roughly half the volume of the medium can be water (water availability fact sheet, http://www.soilquality.org.au/factsheets/water-availability). Even if the porosity of the crater region is relatively low, say 10%, that would still correspond to roughly $5×10^4$ m^3 or $5×10^7$ kg, respectively. I will return to this point later when discussing debris cloud height.

Comparison of empirical and numerical predictions with the observed debris cloud height

In this and the following sections I focus on empirical and numerical estimates of maximum debris cloud height and show that the entrainment of a fixed amount of mass at the beginning of the explosion can explain the relatively low maximum cloud height, approximately 1600 m, that was observed. I find that entrainment of a relatively modest amount of water, possibly from the ammonium nitrate, can explain the lower-than-expected cloud height. Alternatively, a larger amount of dry air/debris or a combination of wet and dry debris, possibly from the crater, can also explain the observed cloud height.

My estimate for the observed cloud height is based on images of the late-time debris cloud in post explosion video footage (e.g., Figure 6). The height of the cloud relative to the buildings in the image on the left suggest a cloud height that is only seven or eight times the height of the tallest building. Based on data from Wikipedia, https://en.wikipedia.org/wiki/List_of_tallest_buildings_in_Lebanon, the tallest building in Beirut is approximately 195 m, limiting the maximum height of the debris cloud to no more than about 1600 m. The image on the right is part of a longer lasting video where the height of the debris cloud has reached its maximum. The similarity of clouds in these images suggests the image on the left also corresponds to a time where the cloud is close to or at its maximum. Even if I increase this cloud height by 25% to account for uncertainties in my estimate, the maximum cloud height would be no more than 2000 m.

Table 3 compares cloud rise predictions

Figure 6. Late-time cell phone images of August 4th, 2020 Beirut explosion debris cloud. Note the maximum cloud height is about 7 or 8 times the maximum height of the buildings on the skyline in the images on the left. (Instagram, August 4th, 2020, YouTube, August 11th, 2020).

from three models. Church's (1969) empirical relationship between the maximum cloud height and yield of a chemical explosion (H=76W*0.25, W in pounds and H in m) suggest we should have seen a maximum cloud height of approximately 3184 m for our preferred yield of 1.4 kilotons: roughly twice my estimate for the maximum cloud height. Similarly, large values are found using a nuclear explosion based empirical model (Harvey et al., 2006) that predicts a maximum height of approximately 3801 m (Table 3). Even the lower bound yield leads to cloud heights well above what was observed. However, most of the data used to calibrate these models were from explosions in dry media and in arid conditions. Furthermore, the comparison with the nuclear explosion based empirical model may not be justified.

Simulations with integral cloud rise models such as DELFIC (Norment, 1977), PUFF (Boughton and DeLaurentis, 1987), and Bubble (Spriggs, 2019) also produced maximum cloud heights that were much greater than those observed. A potential advantage of the integral cloud rise models over the empirical models is that they can account for atmospheric conditions such as relative humidity. However, the high relatively humidity in Beirut exacerbates the difference between the observed and predicted maximum cloud height because the water vapor in the cloud condenses as it rises releasing latent heat which warms the cloud and causes it to rise higher.

Buoyant cloud rise models can also account for effects of the amount and energy released by the explosive mass and entrainment of ambient material during cloud rise. I hypothesize that the Beirut explosion fireball entrained water, air, and debris from the source and/or the near source environment shortly after it detonated and that the water or debris cooled the fireball significantly causing the lower-than-expected maximum cloud height. I tested this hypothesis by modifying Boughton and DeLaurentis's (1987) buoyant cloud rise model (PUFF) for chemical explosions. I modified their algorithm to allow for the initial entrainment of a fixed amount of mass (dry air or water) and implemented the ability to specify the proportion of that mass that was water.

I use this capability to consider two cases, one where the initial injected mass is all dry air and the other where it is all water. For dry air I find that I needed to inject approximately 3.8×10^5 kg of mass to produce a cloud height of approximately 2000 m. I find that more than an order of magnitude less mass is required if I inject water into the fireball instead of dry air or debris (Table 3).

The ability to significantly reduce the maximum cloud height, to a level that is consistent with the observations, by entraining a relatively small amount of water is supportive of the hypothesis that the early entrainment of water caused the relatively low maximum cloud height. The ammonium nitrate explosive may provide the simplest explanation for entrained water since it is known to be hygroscopic, and it sat in the high humidity environment of Beirut harbor for about seven years. Other factors that are consistent with this hypothesis include the explosions proximity to the harbor, a potential source for the water. Similarly, the

Table 3. Empirical and bouyant cloudrise model predictions of maximum debris cloud height.

Yield	Conditions	Church (1969) - max cloud height	Harvey et al (2006)	Modified Boughton and DeLaurentis (1987, this paper)
1.4	Preferred Yield	3184	3801	4960
1.4	Preferred Yield with 3.8×10^5 kg of near-source dry debris			2000
1.4	Preferred Yield with 8.4×10^3 kg of near-source wet debris			2000
0.7	Lower bound yield	2677	2894	3390
2.7	Upper bound Yield	3752	4920	5600

Table 3. Comparison of the observed mushroom cloud height, less than 2000 m, and empirical and numerical model predictions of the mushroom cloud height. Heights based on standard empirical and numerical models are much greater than the height I estimated based on visual observations (cell phone images). Modifications of a buoyant cloud-rise model that accounts for entrainment of water or other debris at the source location can explain the discrepancy between the observed and predicted cloud heights.

ground beneath the explosion may have been a source of water if it had become saturated because of its proximity to the harbor.

Additional visual evidence that may be helpful in constraining the Beirut source

A unique aspect of the Beirut explosion was the rapid availability of satellite data and the large amount of cell phone videos and images. These data may provide useful constraints on the source and the near source environment. In prior sections, satellite and cell phone images have been used to constrain post-detonation crater size and maximum debris cloud height. They can also provide information about the source and near source environment prior to and during the early part of the explosion.

For example, there appears to be a well-defined debris cloud from ground shock (a base surge cloud) running ahead of the fireball in early images of the larger explosion (Figure 7). Directly above and behind this cloud appears to be the start of a condensation cloud and possibly some aerosolized debris. It seems plausible that some of this dust and debris might eventually be entrained by the debris cloud. If so, this could also be a source of material that could be entrained by the fireball.

Figure 7. Early-time image of the large part of the Beirut explosion. Note what appears to be a visible cloud of debris along the ground, some of which might eventually be entrained, that is presumably generated by the advancing shock front.

Future analysis of early images of the fireball (Figure 8) may provide additional constraints on the explosive source and the effects of the near source environment, such as, any effects of nearby structures such as the grain silos at the lower left in the figure or the harbor (not visible in these photos) or the effects of the asymmetric distribution of the explosive in the elongated rectangular warehouse where it was stored. The image on the left in Figure

8 suggests that the grain silos may have blocked some of the very early time effects from the explosion. Perhaps protecting some residents of Beirut. Some asymmetries in the explosion are discernible in the image on the right.

Figure 8. Early images of the Beirut explosion fireball. The very early time image on the left seems to suggest that the large grain silos may have blocked some of the effects from the explosion.

Figure 9 is from a cell phone video that shows what appears to be a large condensation cloud, also known as a Wilson cloud (Waltz, 1975), that formed shortly after the detonation of the larger explosion. Theoretical arguments by Waltz indicate a minimum relative humidity of approximately 70% is needed to form the Wilson cloud, corroborating the estimated near surface relative humidity used to model cloud rise.

Figure 9. A large condensation cloud forms shortly after the main blast in the Beirut explosion. (Instagram, August 4th, 2020, YouTube, August 11th, 2020).

Conclusions

I have used estimates of crater radius from satellite imagery to estimate the yield of the August 4th, 2020 Beirut explosion to be approximately 1.4 kilotons with a lower bound of 0.7 kilotons. This estimate is similar to but slightly larger than those obtained by Diaz, 2021, and Rigby et al., 2020 who used shock wave arrival times to estimate the yield. I suggest that accounting for entrainment of water and/or the relative humidity in the Beirut environment could increase these arrival-time based yield estimates significantly. Estimates from measurements of crater depth and seismic magnitude are also consistent with my crater-size based yield estimates.

I have explained how the crater radius and debris cloud height of this explosion may have been affected by the environment at the source and/or in its vicinity. I presented visual evidence of a maximum cloud height (1600 m) that is much less than predicted by standard cloud rise models. I modified a buoyant cloud rise model to allow for the entrainment of water or dry air at the start of cloud rise and used this modified cloud rise model to show that the entrainment of a relatively modest amount of water at the start of the explosion can explain the observed difference in maximum cloud height. I suggest that entrained water could have come from the ammonium nitrate explosive, the soil beneath the explosion, or the nearby harbor. The hygroscopic nature of ammonium nitrate and the high humidity environment in Beirut harbor suggest that it is a likely source for water entrainment in the fireball. The early-time entrainment of a much larger amount of dry air or debris could also explain the difference between the predicted and observed cloud height.

My observations of the Beirut explosion demonstrate the potential importance of the near-source environment on a variety of explosion related phenomena. An improved understanding of the Beirut explosion can help improve our understanding of the relationship between explosion yield, blast wave damage, crater formation, entrainment, and cloud rise and should help us develop better models for the transport, deposition, and mitigation of debris from explosions.

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Nuclear Deterrence in the Face of Political Instability and Budget Cuts - Opinion

MAJ James J. Rowlands
United States Army Training and Doctrine Command Advanced Civil Schooling – Georgetown University

During the first three months of 2021, it was difficult to follow the news without hearing or reading opinions about what the new Biden administration ought to do regarding nuclear weapons and nuclear deterrence policy. Nearly all these opinions took positions that are decidedly dangerous and anti-nuclear. I am offering the opposing view. I am not writing this purely to voice my opinion, rather I hope to start a discourse that transcends the Countering Weapons of Mass Destruction community. I know that many of this journal's readers are having these conversations, but I hope to expand its reach to our friends, families, and fellow Americans – the ones who vote for the congressional and senatorial leaders that enact, and fund, policies. If we in the community are not educating our fellow Americans, the media will.

There is speculation, and some prodding, amongst the media that the incoming administration will drastically cut the nuclear modernization budget. While there has not yet been an order to conduct a full Nuclear Posture Review, Deputy Secretary of Defense Kathleen Hicks stated that a review is likely.[i,ii] Analyzing media coverage revolving around the budget expenditures on nuclear modernization, a bevy of articles emerge that attempt to underscore why the incoming administration should curtail nuclear modernization investments - there is a preponderance of articles against nuclear modernization.[iii] Journalists, often without the requisite expertise, are penning opinion pieces meant to elicit fear. These articles become a considerable driving force for our populace and congressional leaders.

A challenge to the United States will come from one or more of its nuclear-capable adversaries. Analysts can debate when and how, but hedging nuclear modernization bets on whether the threat manifests later than sooner is strategically irresponsible. The United States cannot assume that it will have ample warning to adjust to an adversary's posture, nor should it presume to have that luxury. Nuclear modernization is not an overnight endeavor that the United States can initiate whimsically "as needed" to meet a threat. The nation must not abandon nuclear modernization in favor of short-term budget solutions or political appeasements.

MAJ. James J. Rowlands is a Nuclear and Countering Weapons of Mass Destruction Officer completing a master's degree in Applied Intelligence at Georgetown University. He has a B.A. in Sociology from Bloomsburg University and a Master of Public Policy & Management from the University of Pittsburgh. Prior to arriving at Georgetown, he served as an MX400 instructor at the United States Military Academy. His email address is james.j.rowlands.mil@mail.mil

Considering deep political divides within the US Government, a decision either in favor of or against further modernization is a tightrope the new administration must walk. The pressure to reverse the previous administration's push for nuclear modernization is political, fiscal, and remains high.[iv,v] The government can and should reduce unnecessary expenditures, but decreasing the nuclear modernization budget broadly is a bad policy. The United States' main competitors, Russia, and China are modernizing their respective nuclear enterprises. Assuming the United States can simply "catch up" to a near-peer adversary's modernization efforts later, or that legacy systems are "good enough" places the country at a distinct long-term disadvantage. Nuclear deterrence is as important today as it was at the height of the Cold War.

In the United States, the American people get a say in how their government operates. The American experiment produced the greatest, most prosperous nation in history, but its system of governance places it at a strategic disadvantage against countries with leaders who do not answer to the people or worry about re-election. Russia and China can enact and implement long-term strategies without fear of political fallout.

Our current political turmoil and national division – some of which our adversaries are responsible for[vi] – is not necessarily enough to invite the "first punch," but it is enough for them to grow more and more provocative in their respective spheres of influence.[vii] Moreover, if the divide proves longer and deeper within the United States, especially if adversarial Information Operation Campaigns continue to succeed in aiding the division, challenging US dominance in other contested domains becomes more likely. The great power competition is well underway; it is not a stretch to say the United States is already losing in the cyber-domain - it should not allow adversaries to bridge the gap in another domain.

President Biden previously stated he envisions a world without nuclear weapons, but that he also understands that the United States needs a strong nuclear deterrent against adversaries' nuclear capabilities.[viii] Although he stated that four years ago, politically it might as well have been 60 years ago. He is under tremendous pressure, both fiscally and politically with looming budget decisions forthcoming.[ix]

Politically, the new administration can score points with its more liberal base on two fronts. Generally, the political left is less inclined to favor nuclear use in any form and canceling a big-ticket item like the Ground-Based Strategic Deterrent (GBSD), the Minuteman III replacement, will make headlines. Second, it underscores a stance that is "anti-Trump" which is also significant for his base. Conversely, initiating deep cuts will open the new administration to scrutiny from the political right that will essentially accuse him of ceding to the anti-nuclear proponents and sending the wrong message to our adversaries.[x]

The United States must look at our modernization efforts from our adversaries' points of view and not the changing political tides at home. Besieging common sense to seize the moral high ground ignores our adversaries' current posture towards the future. We should not be so myopic to think our biggest threats view morality through a Western lens. History underscores our failures in Iraq and Afghanistan because we failed to understand their respective cultures while crafting long-term strategies.

The reality we face as a nation over the next few years' budget cycles is that cutting expensive, long-term projects will look appealing to politicians seeking to replenish the coffers depleted by COVID-19. Funding for the National Nuclear Security Administration's nuclear modernization activities (FY 2021-2025) is $81 billion[xi] and lawmakers have already begun submitting bills to divert nuclear modernization monies to COVID relief and vaccine development.[xii]

To be clear, eschewing nuclear modernization is a mistake that our adversaries are not making. Only now is the military beginning to make up the conventional modernization ground lost to our nearest competitors during the Global War on Terror – the United States cannot afford to let Russia and China outpace us as they modernize their respective nuclear capabilities.[xiii] Budget woes are likely to affect each service in many areas, but where and how the cuts manifest must be strategic and not political.

Recently, US Strategic Command's Commander, Admiral (Adm) Charles Richard gave several interviews stressing the importance of not canceling the GBSD because the Minuteman III is past the point of life extension.[xiv] Adm. Richard further underscored that Nuclear Command, Control, and Communications (NC3) investments are just "…as important to the strategic deterrence mission as the delivery systems and the weapons complex and we are in equal need to recapitalize it alongside the delivery systems."[xv]

The NC3 is a complex system with many moving parts, but because it lacks the high profile of the GBSD it is in many ways more susceptible to underfunding. Considering our current antiquated NC3 system is susceptible to intrusion from our adversaries' cyber-capabilities, upgrading our NC3 system is paramount to the overall success of our nuclear deterrence. If some of the most current systems fail under dedicated cyber-attacks from adversaries how can we expect Cold War-era relics to stand a chance when it matters the most?

Nuclear deterrence prevents our near-peer adversaries from throwing the proverbial "sucker punch" and the nuclear enterprise deters our lesser adversaries from using nuclear weapons. Both Putin and Xi are pragmatic, rational leaders of their respective countries. Neither will escalate to nuclear unless they believe they have more to gain than they risk losing. We address this by 1) imposing unacceptable costs – maintaining the ability to counter-strike and 2) denying benefits – defending in a manner that makes the adversaries question whether the attack would achieve their desired objectives.

Think about this: Conventionally, the United States can fight Russia or China and win. A conflict with either country would be costly in both lives and dollars, but the likelihood of victory remains high.[xvi] The United States cannot fight Russia and China and win, however. While Russia and China are not currently formal military allies, their cooperative military engagements have increased in size and scope over the last few years. Adversaries of the United States are also exploring limited nuclear options[xvii, xviii] and our ability to fight and win starts with ensuring our NC3 systems and equipment are adequate to allow the United States Military to shoot, move, and communicate in a non-permissible nuclear environment.

Our nuclear deterrent strategy, or conventional strategy for that matter, cannot be a "one size fits all approach." What deters Russia may not deter China and vice versa. To borrow a term from boxing, styles make fights. On paper, a challenger may look like the lesser opponent, but their unique style may present a challenge for the favorite. Attempting to man, train, and equip the military in the same way for all opponents leaves them susceptible to the unorthodox challenger they failed to anticipate.

The fact remains that a challenge to US dominance will eventually come. What is unknown is whether that fight will be purely conventional, nuclear, or limited-nuclear in scope and above all, if the United States will be "ready" for it. As the US Army begins posturing towards future conflicts, US nuclear deterrent capabilities keep the nation's adversaries about as honest as they are ever going to be. An adversary will strike the United States when they believe they are ready. The only unknown is who and whether it is an anticipated first punch or a sucker punch that catches the United States flat-footed. To be clear, North Korea and Iran are threats as well that the United States cannot ignore, but they are not “pacing” threats like Russia or China.

The United States will not have the luxury of postponing conflict until it decides its readiness is on par with that of its enemies. Investing in the modernization of its nuclear arsenal sends a clear message to any adversary thinking they may be ready to tussle with the United States of America. How the United States approaches nuclear modernization will likely determine how its adversaries operate in other contested domains. Nuclear modernization should not become political fodder, but rather serve to ensure our freedoms and the American way of life.

Notes

i. Bender, Bryan. “Hicks Raises Prospect of Defense Cuts,” February 3, 2021. There has also been some speculation that if a new administration undertakes an NPR that it may only be targeted and not full scope in nature.

ii. Reif, Kingston. “Arms Control Today.” Pentagon Reviews Nuclear Budget | Arms Control Association, April 2021.

iii. This statement regards “mainstream” print media. Nearly all widely circulated print media outlets have penned articles against nuclear modernization, save for a few conservative outlets.

iv. Everstine, Brian. “STRATCOM Welcomes Nuke Review but Says Minuteman III Life Extension Should Not Be Considered.” Air Force Magazine, January 6, 2021.

v. Gordon, Michael R. “Biden to Review U.S. Nuclear-Weapons Programs, With Eye Toward Cuts.” The Wall Street Journal. Dow Jones & Company, December 24, 2020.

vi. “US Election 2020: China, Russia and Iran 'Trying to Influence' Vote.” BBC News. BBC, August 8, 2020.

vii. China is increasing provocation in the South China Sea, and recently Russia has begun massing on the Ukrainian border. Neither country thus far has faced any real disincentive to stop. Middendorf II, J. William. “China and Russia: Two Big Threats the U.S. Military Can't Ignore.” The Heritage Foundation, February 2, 2021.

viii. “Remarks by the Vice President on Nuclear Security.” National Archives and Records Administration. National Archives and Records Administration, January 12, 2017.

ix. The defense budget is expected to be revealed May 3rd. Reif, Kingston. “Arms Control Today.” Pentagon Reviews Nuclear Budget | Arms Control Association, April 2021.

x. Both scenarios are currently playing out in congress along party lines. Kheel, Rebecca. “Lawmakers Gird for Spending Battle over Nuclear Weapons.” The Hill. The Hill, March 7, 2021.

xi. National Nuclear Security Administration: Information on the Fiscal Year 2021 Budget Request and Affordability of Nuclear Modernization Activities. GAO-20-573R. (P. 7)

xii. Two separate bills have been submitted by Democratic lawmakers. One aims to curtail sea-based cruise missile development and the other aims to halt modernization of the Minute Man III replacement. Gould, Joe. "Lawmakers Aim to Prevent Sea-Based Nuclear Cruise Missile." Defense News. Defense News, March 4, 2021. & Insinna, Valerie. "A New Bill Would Defund New ICBMs to Pay for Coronavirus Vaccine Research." Defense News. Defense News, March 26, 2021.

xiii. Hitchens, Theresa. "2021: Air Force's Nuke Mod Efforts Service's Biggest Challenge." Breaking Defense. Above the Law, December 30, 2020.

xiv. Everstine, Brian. "STRATCOM Welcomes Nuke Review but Says Minuteman III Life Extension Should Not Be Considered." Air Force Magazine, January 6, 2021.

xv. USSTRATCOM interview with Adm. Richard. "Interview with the Defense Writers Group - Adm. Charles Richard, Commander U.S. Strategic Command." U.S. Strategic Command, January 8, 2021.

xvi. This statement assumes that in the event of a conflict with either Russia or China the US would have the will to see it through. War is a contest of wills, and in either scenario the US would have to be willing to see it through.

xvii. Limited Nuclear Options is a military strategy from the Cold War that envisioned a direct confrontation between the two nuclear superpowers (i.e., the Soviet Union and the United States) that did not necessarily end in either surrender or massive destruction and the loss of millions of lives on both sides. The limited nuclear options (LNO) approach allowed a country's military commanders to shift the targeting of nuclear missiles from enemy cities to enemy army installations, thereby limiting the effects of such a war. "Limited Nuclear Options." Encyclopedia Britannica. Encyclopedia Britannica, inc.

xviii. Nuclear posture review 2018, p 81

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CBRN Vignette 20-1 “Contaminated Convoy”

LTC Daniel P. Laurelli
United States Army Nuclear and Countering WMD Agency (USANCA)

Author’s Solution:

Background:

At the request of the Transican government, the United States deployed Joint Task Force (JTF) Protector to assist in stabilizing the nation of Transia. The Transican military, with assistance of national police force and local militias, recently prevailed from a violent civil war, culminating in a major force-on-force engagement. As a result, the nation’s military and infrastructure was heavily damaged. JTF Protector was deployed at the request of the Transican government to provide humanitarian assistance to civilian population and military assistance to the battered Transican military and local pro-government militias.

Situation: You are the Commander of the 55th Chemical Company (Area Support) in support of JTF Protector. Due to the high demand for convoys to government friendly population centers, you were placed in charge of Convoy 55 to resupply the village of Trabók using Main Supply Route (MSR) Red. It is critical the water and cargo reaches its destination.

Friendly Forces: The three Decontamination Platoons were detached from the 55th Chemical Company (CS) to support Logistics Base (LOGBASE) Wolverine located east of Figure 1 (Convoy 55 Map and Overlay). For additional security above the two operational Nuclear, Biological and Chemical Reconnaissance Vehicle (NBCRV) Strykers, the 5th Infantry Division (ID) attached two infantry-configured Strykers, without their dismounts. For transporting supplies, Convoy 55 is composed of a cargo truck platoon with 8 cargo Heavy Expanded Mobility Tactical Truck (HEMTT) and a water truck platoon with 8 potable water HEMTT tankers (Table 1 – Convoy 55 Laydown and Figure 2 – Convoy 55 Organization). The local militia Transian (pro-government) Infantry Battalion is securing the village, but it is not well-trained or supplied. The village is under harassment from insurgent cells.

LTC Daniel Laurelli is a Countering Weapons of Mass Destruction (CWMD)/ Chemical, Biological, Radiological, and Nuclear Defense (CBRND) Officer at the US Army Nuclear and Countering WMD Agency (USANCA), in Fort Belvoir, VA. He has a B.A. in Biochemistry from Ithaca College, and a M.S. in Environmental Management from Webster University. He was previously assigned as a Chemical Officer at the 55th Medical Group, 101st Chemical Company, 3rd Infantry Division (M) Aviation Brigade, US Environmental Protection Agency (EPA) in Region 7, US Army CBRN School, and the Defense Threat Reduction Agency (DTRA). His email address is daniel.p.laurelli.mil@mail.mil.

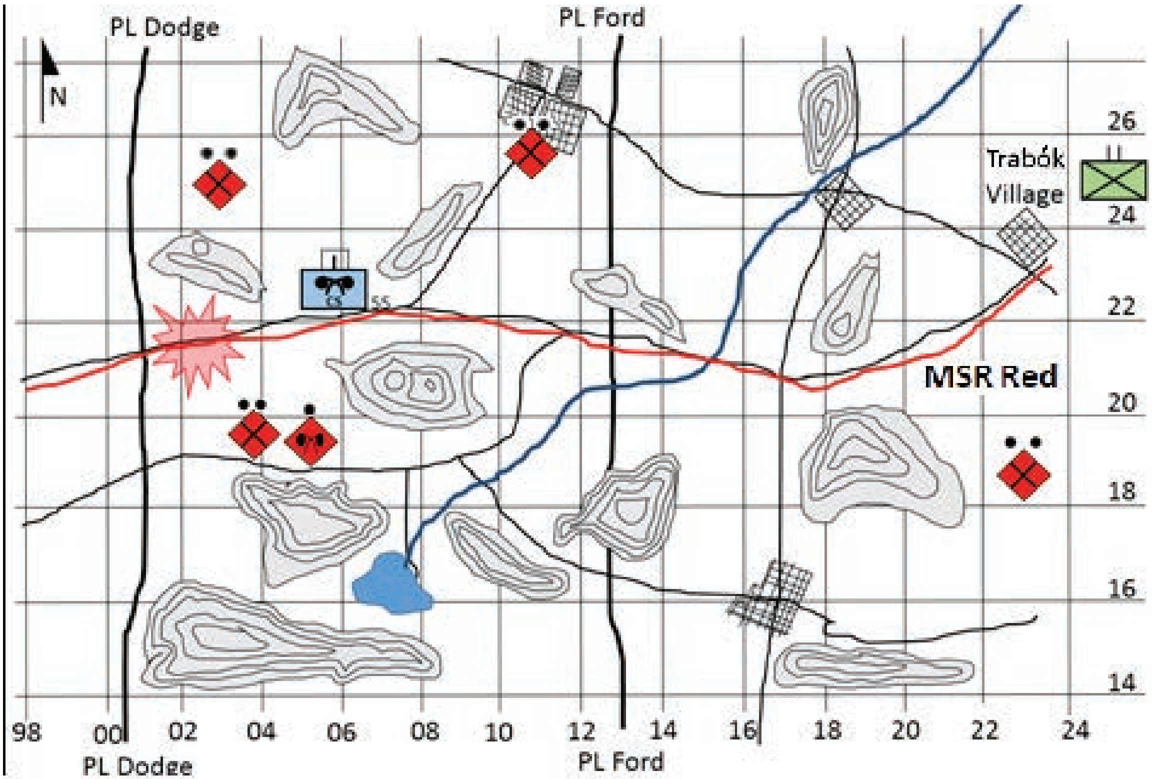

Figure 1 – Convoy 55 Map and Overlay

Enemy Forces: JTF Protector Area of Responsibility (AOR) of Transia has significant insurgent elements (up to team size). As a result of the loss of the force-on-force battle, some elements of the opposing force has taken to insurgency tactics. These insurgent elements operate throughout the countryside reducing freedom of movement between population centers. Unconfirmed intelligence reports (low confidence) state some insurgence elements have acquired a small stockpile of un-weaponized (bulk) HD mustard agent in another Division's AOR. The JTF Protector S-2 (Intelligence Section) determined if reports are true, the insurgency lacks transportation assets to move it into the 5th ID AOR or the CBRN expertise to employ it.

Incident: Convoy 55 drives through HD Mustard agent dumped on the road by the insurgents. Convoy 55's mission to village of Trabók is critical. There is no friendly forces in the AOR, except for the local militia securing the village. Convoy 55 halted just north of MSR Red at 045221, with reports of unusual smells, irritation on exposed skin, scratchy throats and burning eyes. The undercarriages and tires of all convoy vehicles are contaminated. Convoy personnel have their protective masks but only one set of Mission Oriented Protective Posture (MOPP) gear. The insurgent teams increase their patrols for militia, convoys, and supplies at night. No friendly forces are available until the next day to provide assistance. The two infantry Stryker vehicles identified at least two insurgent teams using mountains to maneuver closer to the stopped convoy.

Weather: It is a cold February in Transia with a high of 50 degrees F. The sun sets at 1730 and projected nighttime low of 40 degrees F with possibility of light rains after midnight.

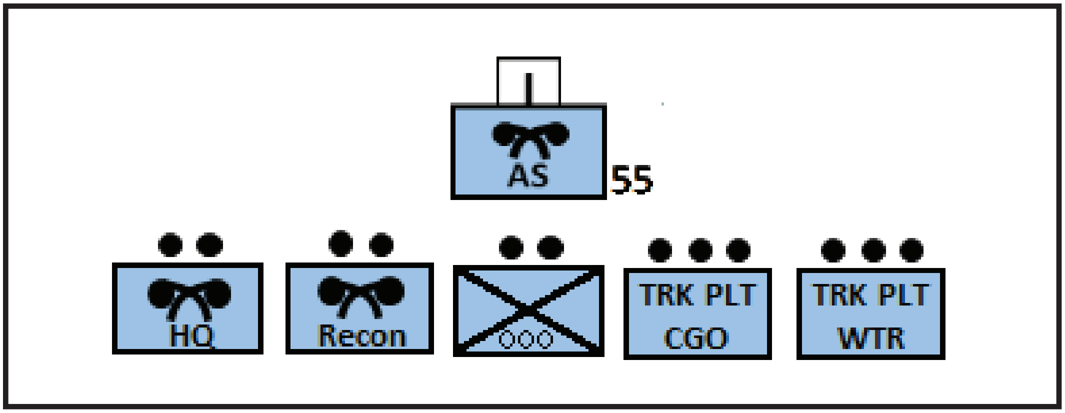

Figure 2 – Convoy 55 Organization

Element	Vehicle Type	Amount	Personnel
HQ	HMMWV (CMD)	2	4
5th ID	Stryker (Security)	2	8
Co	Fuel Truck (LTV)	1	2
Co	Wrecker (HEMTT)	1	2
Recon TM	Stryker NBCRV	2	6
TRK PLT 1	Transport Truck (HEMTT 2,500gal)	8	24
TRK PLT 2	Cargo Truck (HEMTT)	8	24
		TOT	TOT
		24	70

Table 1 – Convoy 55 Laydown

Commander, Convoy 55:

Mission: Convoy 55 dons MOPP 4, conducts individual/crew decontamination at current location, then moves to vicinity 080230 to conduct ad hoc operational decontamination to reduce contamination on vehicles prior to continuing to the village of Trabók.

Intent: My intent is for all personnel not in overpressure systems in Convoy 55 to don MOPP 4 then conduct individual/crew decontamination to protect the soldiers from continued exposure. While at the first location, I will send CBRN 1 report to Logistic Base (LOGBASE) Wolverine and the Militia Battalion Headquarters at the village of Trabók. I will request Trabók prepare for medical treatment and decontamination as needed at a reception point outside the village but within the militia perimeter. The Strykers, with their overpressure systems, are used to maintain situation awareness and security against insurgence teams. Additionally, the Strykers will lead the Convoy at best possible speed to Trabók. Convoy 55 moves to crossroads to conduct a hasty operational decontamination of the undercarriages of the HEMTT and HMMWVs, using as little water as possible and potentially allowing drivers to remove masks if needed while driving. Once decontamination is complete, the Stryker vehicles will lead the convoy as quickly as possible to the outskirts of Trabók to coordinate contact with the Transian militia. Once within the security perimeter, Convoy 55 personnel will conduct thorough decontamination operations and ensure all personnel receive medical treatment. I will report status of Convoy 55 to LOG-

BASE Wolverine and have cargo vehicles unloaded and secured to reduce any additional spread of chemical agents and off-gassing.

Tasks:

Task: Instruct personnel that did not exit vehicles with overpressure systems (Strykers) to not exit vehicles

Purpose: To reduce contamination and protect solders from further contamination

Task: Direct personnel not in Stryker vehicles to don MOPP 4 and conduct individual/crew decontamination

Purpose: To reduce contamination and protect solders from further contamination

Task: Continue moving on MSR Red to vicinity 111229 near cross roads

Purpose: To move away from immediate insurgent threat

Task: Water Transport platoon set up an ad hoc operational decontamination site at vicinity 111229

Purpose: To remove gross contamination from the HEMTT and HMMWVs undercarriages

Task: NBCRVs mark decontamination site prior to departing the area

Purpose: To prevent spread of chemical agent and contamination of other personnel and vehicles

Task: Convoy 55 continues movement to outskirts of Trabók for medical treatment and decontamination

Purpose: To removal as much contamination as possible and allow the cargo vehicles to be unloaded with lower risk to personnel

Task: Segregate vehicles in Trabók until addition guidance and forces are available

Purpose: To minimize spread of chemical agents and off-gassing

Rationale:

1) The convoy commander's immediate need is to protect personnel from HD exposure and use any organic assets the convoy has to decontaminate personnel and vehicles to prevent spread of the chemical agent.

2) The convoy commander needs to report the situation and provide a CBRN-1 report to Local Militia at Trabók and higher headquarters at LOGBASE Wolverine. Higher headquarters will be able to assemble a task force to decontaminate the terrain, secure the MSR from insurgents, treat/recover the causalities, and thoroughly decontamination convoy vehicles.

3) The recon team must be sent to mark the area to prevent others from entering the contaminated area, for both the additional relief columns and for any locals.

4) While the use of potable water from the transport platoon is a commander's call and will create an area of contamination, it is critical to remove as much contamination as early as possible to reduce potential exposure and spread of the agent to the soldiers and driving cabins. Lowering the contamination level will speed up the weathering effect of the agent before reaching the village perimeter, reducing the potential to spread contamination further. Using the side road and hill at vicinity 111229, near the crossroads, to establish an off-road decontamination site will further reduce the risk of contamination.

Sources:

ATP 3-11.32 Multi-Service Tactics, Techniques, and Procedures for Chemical, Biological, Radiological, and Nuclear Passive Defense

ATP 4-01.45 Multi-Service Tactics, Techniques, and Procedures for Tactical Convoy Operations

ATP 4-11 Army Motor Transport Operations

FM 3-11 CBRN Operations

CBRN Reporting GTA

CBRN Vignette 21-1 "Division Brief"

LTC Daniel P. Laurelli
United States Army Nuclear and Countering WMD Agency (USANCA)

This CBRN vignette is part of an ongoing series of scenarios developed as a training tool for decision makers at all levels – tactical to strategic. The goal is to foster both thought and discussion, and to support training. Readers are encouraged to send possible solutions to the Countering WMD Journal as a means of interaction with the CBRN community. The author's solution, along with selected readers' solutions, will be published in future journal issues.

Background:
The U.S. Army 5th Mechanized Division deployed to the nation of Transia as part of Combined Joint Task Force (CJTF) Freedom with the mission to conduct offensive operations against the forces of Donovia. The 1st (French) Armored Division is to the north and 3rd (United Kingdom) Armored Division is to the south of the U.S. Army 5th Mechanized Division. The U.S. Army 3rd Infantry Division is staged in tactical assembly areas (TAAs) to the west.

Situation:
It is 12 Apr 2024 and you are the new CBRN officer for the U.S. Army 5th Mechanized Division deployed to Transia. Having just arrived, you are directed to attend the divisional operations order brief, which is about to start. The division staff is briefing the Commander, U.S. Army 5th Mechanized Division (Major General Smyth) the plan to conduct offensive operations. As you take a seat, the G-2 (intelligence officer) begins with the enemy situation followed by the G-3 (operations officer), the weather officer, the fires officer, and the sustainment officer (G-4).

G-2 (Intelligence):
The enemy forces (Donovian 46th Mech-Armor Division) are in the U.S. Army 5th Mechanized Division area of responsibility (AOR) and possess a (near peer) credible threat. The Donovian 46th Mech-Armor Division has two organic artillery batteries (12 x 122mm and 4 x 152mm per battery). The nation of Donovia possesses chemical weapons and has a policy for use as a defensive combat multiplier. At the division level, Donovian Tactics, Technics, and Procedures (TTPs) include targeting maneuver elements in the open and as final protective fire (FPF) in order to allow brigades engaged in combat to fall back to

LTC Daniel Laurelli is a Countering Weapons of Mass Destruction (CWMD)/ Chemical, Biological, Radiological, and Nuclear Defense (CBRND) Officer at the US Army Nuclear and Countering WMD Agency (USANCA), in Fort Belvoir, VA. He has a B.A. in Biochemistry from Ithaca College, and a M.S. in Environmental Management from Webster University. He was previously assigned as a Chemical Officer at the 55th Medical Group, 101st Chemical Company, 3rd Infantry Division (M) Aviation Brigade, US Environmental Protection Agency (EPA) in Region 7, US Army CBRN School, and the Defense Threat Reduction Agency (DTRA). His email address is daniel.p.laurelli.mil@mail.mil.

alternative fighting positions. The Donovian 46th Mech-Armor Division is assessed as proficient in conducting operations in a chemically contaminated environment, to include decontamination (Table 1: Donovian 46th Mech-Armor Division). Intelligence confirmed that each battery has several chemical munition ammunition vehicles in staging areas, each equipped with significant chemical munitions (mustard and nerve agent). Additionally, there are three chemical munition storage sites in the AOR containing munitions with mustard and nerve agent (Table 2: Chemical Munition Storage Sites). Each 46th Mech-Armor Division Brigade is composed of two mechanized battalions and one armor battalion. Brigade 2 has been reinforced with an additional mechanized battalion and an armor battalion (See Figure 2: Donovian 46th Mech-Armor Division)

Target	Location (Grid)	Location Description	Unit/Site Description
46th Mech-Armor Division CP	6030	PL Dodge	Command and Control (PL Dodge)
Brigade 1	2535	East of Village (Southern part of AO)	Mech Armor BDE
Brigade 2	2525	West of River (Center part of AO)	Mech Armor BDE
Brigade 3	3015	Mech Armor BDE (Northern part of AO)	Mech Armor BDE
Battery 1	3535	East of Village	12 x 122mm and 4 x 152mm per battery
Battery 2	5040	East of Village	12 x 122mm and 4 x 152mm per battery

Table 1: Donovian 46th Mech-Armor Division

Chemical Site Locations: The Donovian 46th Mech-Armor Division maintains three chemical munition storage sites. The Donovian 46th Mech-Armor Division Chemical Company is composed of two chemical munition transportation platoons and three heavy decontamination platoons.

Chemical Site 1 is a back-up chemical weapons storage site for the Donovian 46th Mech-Armor Division. It is composed of 100 well camouflaged munition bunkers. The bunkers are rater for protection from small arms fire. A chemical munitions and security unit maintains the site.

Chemical Site 2 is the main chemical weapon storage site for the Donovian 46th Mech-Armor Division. A chemical munitions and security unit maintains the site. The site is split into two areas. Site A is 150 ammunition bunkers, able to protect munitions from most artillery attacks. Area B is a temporary storage area, which is a football field sized area with a berm and 6-foot fence, where the chemical munitions unit prepares to rounds for transfer to the Donovian chemical artillery units.

Chemical Site 3 is a small forward base for the Donovian 46th Mech-Armor Division. The chemical munitions along with conventional munitions are stored in a large warehouse with a perimeter defense and berm. The site is secured by local police.

Target	Location (Grid)	Location Description	Munitions Inventory
Chemical Storage Site 1	4515	East of City	50 x 122mm nerve artillery shells 50 x 122mm mustard artillery shells 100 x 152mm nerve artillery shells 100 x 152mm mustard artillery shells
Chemical Storage Site 2	5540	Northeast of Town	Munitions at Area A contains: • 200 x 122mm nerve artillery shells • 200 x 122mm mustard artillery shells • 200 x 152mm nerve artillery shells • 200 x 152mm mustard artillery shells Munitions at Area B contains: • 50 x 122mm nerve artillery shells • 50 x 122mm mustard artillery shells • 50 x 152mm nerve artillery shells • 50 x 152mm mustard artillery shells
Chemical Storage Site 3	3040	Southeast of City	50 x 122mm nerve artillery shells 20 x 122mm mustard artillery shells 100 x 152mm nerve artillery shells 50 x 152mm mustard artillery shells 100 x 500lb bombs 50 x 1000lbs bombs 8 x 2000lb bomb 300 x 240mm rockets

Table 2: Chemical Munition Storage Sites

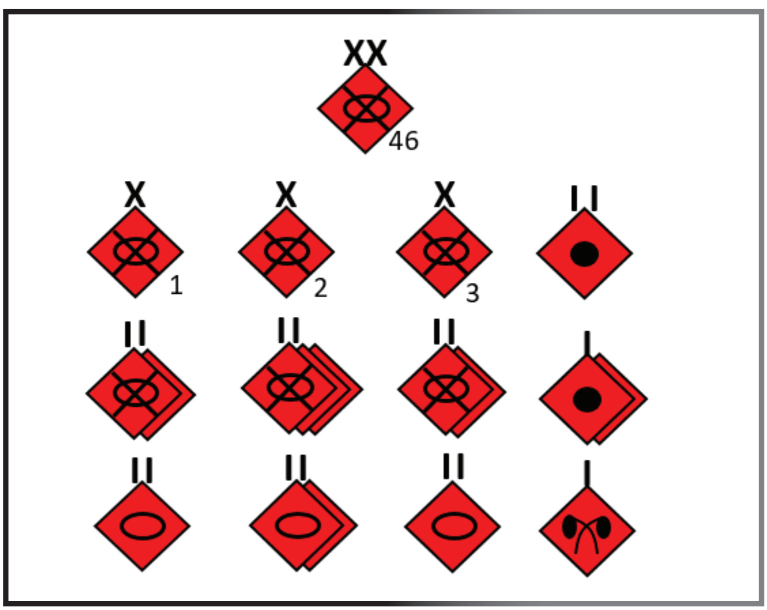

Table 2: Chemical Munition Storage Sites

G3 (Operations):[1]

Mission: At 043015Apr2024 the U.S. Army 5th Mechanized Division with three Armored Brigade Combat Teams (ABCT) attack from line of departure phase line (PL) Ford with a limit of advance of PL Dodge in order to destroy the Donovian 46th Mech-Armor Division and establish a covering force NLT 180020 Apr2024 in the U.S. Army 5th Mechanized Division Area of Operations (AO) secure the terrain west of PL Dodge. Establish Area defense along PL Dodge. On order, U.S. Army

5th Mechanized Division will conduct forward passage of lines for the U.S. Army 3rd Infantry Division (Figure 1: US 5th Mechanized Division Operational Sketch) to continue offensive operations.

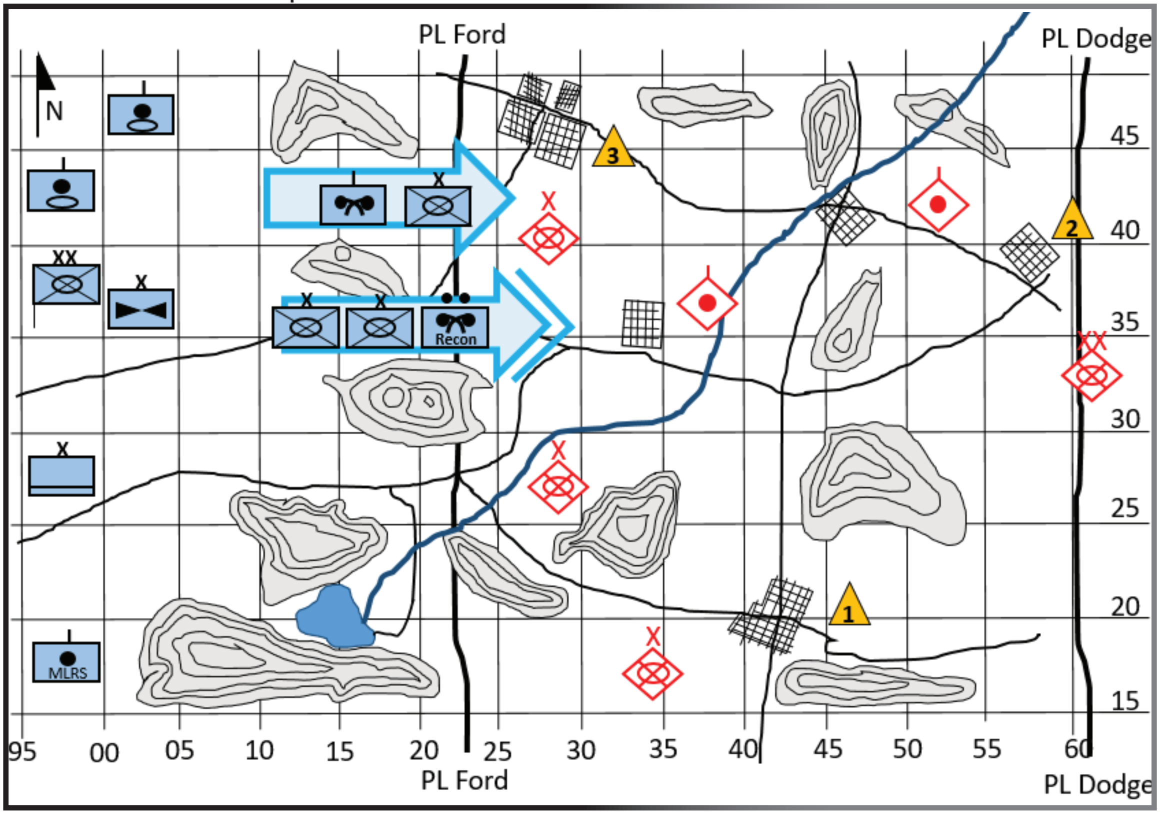

Figure 2: U.S. Army 5th Mechanized Division Operational Sketch (not to scale)

Task Organization:

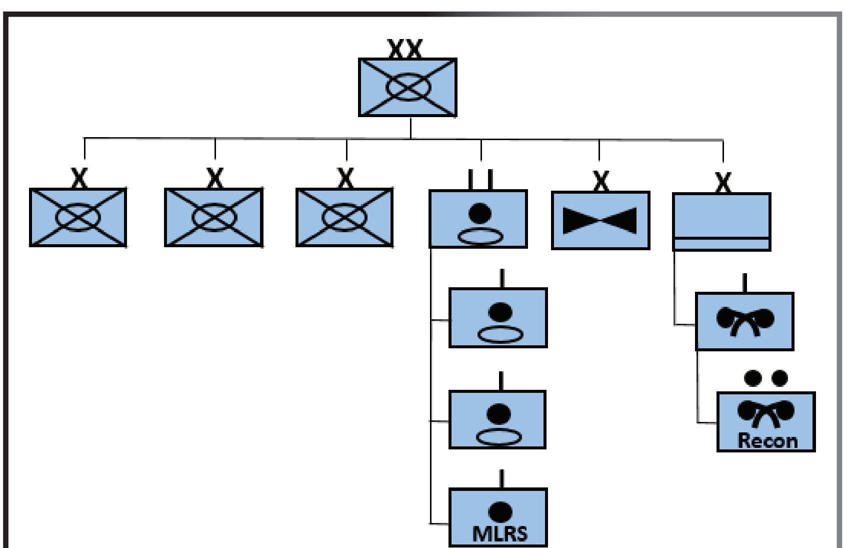

Figure 3: U.S. Army 5th Mechanized Infantry Division

Commander's intent:
Swiftly attack to destroy the Donovian 46th Mech-Armor Division to PL Dodge, establishing a area defense to facilitate forward passage of lines of the U.S. Army 3rd Infantry Division NLT 200018Apr2024. We will avoid chemical weapon use by suppressing enemy fires with U.S. Army 5th Mechanized Division Fires Battalion, swiftly closing and destroying Donovian combat elements, by passing urban areas to maintain operational tempo and securing chemical munition storage sites for follow-on destruction. The U.S. Army 5th Mechanized Division end state is the secure the terrain west of PL Dodge and prepared to conduct forward passage of lines.

Task to subordinate units:
1st BCT with the 55th Chemical Company (-): As supporting effort, advance on the northern axis as the main attack by engaging and destroying the Donovian 46th Mech-Armor Division (Brigade 3) in their axis of advance en route to PL Dodge.
2nd and 3rd BCT: As the main effort, advance along the southern axis as the main effort to engage and defeat the 46th Mech-Armor Division (Brigade 2) and the 46th Mech-Armor Division Command Post (CP)
Combat Aviation Brigade: Provide two attack (AH-64D) companies to main effort, one attack (AH-64D) company to supporting effort, and keep one attack (AH-64D) company as division reserve.
5th Mechanized Division Field Artillery Battalion: Conduct counter fire, long range precision fires and close combat operations.
55th Chemical Company (NBCRVs): Provide overwatch to the main effort and be prepared to mark lanes clear of contamination in support of 2nd and 3rd BCTs.

Division Fires:
As part of the preparatory fires (0300 – 0430 15 Apr 2024), the U.S. Army 5th Mechanized Division Multiple Launch Rocket System (MLRS) and 155mm batteries priorities of effort is:

1) Donovian artillery batteries;
2) Donovian chemical transportation munition trucks;
3) Chemical munitions storage sites; and
4) 46th Mech-Armor Division Command Post.

At 0430 the MLRS and one 155mm battery priority of fires is 2nd BCT as lead element, followed by 3rd BCT. One 155mm battery priority of fires is 1st BCT.

Division Weather:
Transia is in its dry season with no rain predicted and little cloud coverage (Table 3: Weather Forecast). On the morning of the offensive, the temperature is forecasted to be 50 degrees F, 60% humidity, and steady wind from the east at 11 kph.

Date	Temp °F (Low)	Temp °F (High)	Precipitation %	Cloud Cover %	Wind Speed (kph)
15 Apr 2024	48	55	15	5	11
16 Apr 2024	47	54	10	10	14
17 Apr 2024	48	56	5	5	8
18 Apr 2024	48	57	10	15	12
19 Apr 2024	47	58	15	10	7
20 Apr 2024	49	59	15	15	13

Table 3: Weather Forecast

G-4 (Sustainment Officer): The U.S. Army 5th Mechanized Division Sustainment Brigade will provide all classes of supply to the division with priority to the three ABCTs, followed by the fires brigade, and the aviation brigade. The maneuver company supply trains are responsible for the second CBRN protection gear set, with the sustainment brigade maintaining additional CBRN protection gear and decontamination supplies at Tactical Assembly Area (TAA) Wolverine.

Requirement:

After reviewing the situation, write a point paper to the Divisional Commander about the divisional offensive plan, as briefed. Readers wanting to submit solutions can send them to USANCA care of daniel.p.laurelli.mil@mail.mil.

References:

Army Doctrine Publication (ADP) 3-90 Offense and Defense, 31 July 2019

TRADOC Pamphlet 525-3-6 U.S. Army Functional Concept for Movement and Maneuver (AFC-MM) 2020 - 2040, Feb 2017

A Review of Research Conducted by FA52 Students during 2020

MAJ Joshua D Frey
United States Army Student Detachment

Every year, the U.S. Army Nuclear and CWMD Agency (USANCA) supports FA52 officers pursuing graduate studies through the Army's Advanced Civil Schooling program. These studies are an important stage in the professional development and broadening of newly assessed FA52s and provide a common grounding experience in an academic discipline related to WMD science or policy. While the future career path of these officers may or may not be related to their chosen field of research, their efforts to improve the common understanding of physical phenomena within our universe, as well as the social and political interactions that affect our national security, are important and cannot be dismissed.

The purpose of this article is to provide a short summary of the work completed over the past year by FA52 students, from the March 2020 through March 2021. The abstracts for their theses, dissertations, or capstone projects are grouped by subject matter. Research directly related to Nuclear Science and Engineering are first, followed by research focused on Chemical and Materials Science, then research in the Biological Sciences, and finally research in Policy and International Relations. Finally, this author takes no credit for the work of the officers whose abstracts appear in this article and appreciates their assistance in providing their abstracts and the URLs for their theses and journal articles. Those officers whose e-mails are listed may be contacted directly with questions regarding their research.

FA52 officers graduating during 2021 from ACS, SAMS, or other academic programs with a research component are invited to send this author a 200-word abstract and a URL to their document for future editions of this article.

MAJ Joshua Frey is a Graduate Student at the Air Force Institute of Technology, at Wright-Patterson Air Force Base, OH with a follow-on assignment to the DTRA-NSERC at West Point, NY. He has a B.A. in Physical Sciences and Religion from Ripon College, and M.S. degrees in Environmental Management, International Relations, Nuclear Engineering, and Materials Science from Webster University, Troy University, and the Air Force Institute of Technology, respectively. He was previously assigned as a G5 CWMD Planner and Nuclear Disablement Team Operations Officer at the 20th CBRNE Command, Operations Officer and CBRNE Response Team Leader at 23d CBRNE Bn, 2ID, and CBRN Reconnaissance Platoon Leader at 3d CR. His email address is Joshua.d.frey4.mil@mail.mil.

Nuclear Science and Engineering

Fieldable Neutron Imaging System: Simulation and Experimentation into the Viability of Associated Particle Imaging in Austere Field Environments

CPT Benjamin Troxell
benjamin.c.troxell.mil@mail.mil

This thesis is the culmination of an effort to develop a portable fast neutron radiography device capable of generating images of the internal structure of high Z objects non-intrusively in austere field environments. This work represents the first advancement to this end for the Fieldable Nuclear Materials Identification System (FNMIS). The effort was two pronged in its approach. First, a physical system was constructed and tested in an effort to reduce size and overall system weight. Simultaneously, a new simulation workspace was developed to test objects unavailable for physical imaging. The physics of the simulation were modeled utilizing the latest version of Monte Carlo N-Particle Transport (MCNP) 6.2. Post processing and image reconstruction were completed utilizing Python 3.7 employing the mcnptools module to study the content of MCNP's particle track (PTRAC) file. As part of this simulation process, a new beam characterization profile for the Russian ING-27 DT generator has been developed. The result is a double gaussian fit comparable to the characterization of the Thermo Scientific API-120 system. A series of objects and misalignment experiments were conducted. The result of this work is an agreement between the results of simulations and those of the laboratory measurements. Significant advances in setup time, alignment techniques, and required time of exposure were all made as part of the construction process. This work paves the way for the application of neural networks to improve misalignment assessment and image quality.

https://trace.tennessee.edu/utk_gradthes/5587/

Effects of Water Entrainment on Shock Propagation from a Nuclear Detonation

MAJ Trenton Freeman

Films recorded during the period of atmospheric nuclear testing in the United States remain one of the only sources of data gathered during nuclear testing. Over 10,000 films are being scanned and digitized at Lawrence Livermore National Laboratory for more thorough analysis with modern image processing techniques in an attempt gain a more comprehensive understanding of various nuclear phenomena. This research leveraged historic nuclear test films detonated from barges in the Pacific Ocean to quantify how water entrainment, energy transmission, and drag effects impact shock wave propagation from the time of detonation to the time of first thermal minimum, tmin. The radius and height of the shock wave during times of interest was identified through digital image processing techniques, and cube root scaling laws were applied to determine the apparent yield lost and percentage of yield lost at the water's surface from the cumulative effects of the loss terms identified above. Finally, a high-fidelity multi-physics software package particularly appropriate for solving problems related to high-explosive and nuclear detonations in two and three dimensions known as SHAMRC or Second-Order, Hydrodynamic, Automatic Mesh Refinement Code was used to simulate a nuclear detonation with a similar yield to a historic test to determine how well current models incorporate water entrainment, energy transmission, and drag effects.

Available at https://discover.dtic.mil/

Decoupling of Underground Nuclear Detonations

MAJ Lawton Drake

The ability of a nation to develop a clandestine weapons program exists when that nation develops the capability to design low-yield devices that are able to be detonated underground where the seismic signals are mitigated through the surrounding geologic medium. In this experiment a 1.57 kiloton boosted fission device was developed based upon known principles and placed in an air cavity surrounded by a salt dome similar in design to the Salmon/Sterling event conducted near Hattiesburg, Mississippi. The resulting pressure and energy waves, 28.77 Mbar, and6.58e7 Mbar-cm3, respectively, were measured against a uniform salt medium and its elastic limits. The measures were found not to exceed the elastic limits of the salt medium which validates the theory of decoupling nuclear explosives in lighter than heavy-rock mediums. Based upon these limits, the pressure waves were measured against known seismic networks, namely, the World-Wide Standardized Seismograph Network, which was developed out of the 1958 Geneva Conference and put into service in 1967. This network is able to positively identify earthquakes of magnitude 4.75, which is roughly equivalent to a 20-kiloton device, far below the threshold created by a 1.57 kiloton device. Therefore, it can be shown that a boosted fission weapon with a yield of 1.57 kilotons would be able to escape detection by known seismic systems through the use of decoupling methods.

Isolation, Characterization and Analysis of BOMARC Accident Debris

MAJ Aaron Heffelfinger

Accidents involving nuclear weapons, such as the Boeing Michigan Aeronautical Research Center (BOMARC) accident in 1960, always pose a significant risk of allowing particles composed of nuclear materials to enter the environment. These particles often differ in characteristics and can be of greatly varying sizes; some are large enough to see with the naked eye and others are so small they pose a substantial inhalation risk. While numerous government agencies have conducted soil remediation/surveys at the BOMARC site, radioisotopes remain behind in the soil. Gamma ray analysis was conducted on the soil samples and calculations based on the presence of 241Am confirmed the previously determined weapons grade plutonium activity within the environmental sample. While testing two very different non-destructive methods for the separation of hot particles, this research isolated 70 actinide particles ranging in diameter from 1 to 34 μm from a sample resultant from the conflagration of a nuclear weapon and subsequent firefighting. These particles underwent significant analysis that included both morphological and elemental characterization. Morphological trends indicated particles across the four evaluated size distributions had similar circularity and found three major particle types present based on shape, angularity, and surface features. Elemental analysis indicated the presence of uranium in all 70 particles and identified trends of other major and trace elements within these particles.

Pending availability at https://scholar.afit.edu/

Effective Dose Calculations for Weapons Disassembly Procedures via MCNP

CPT Sean Fitzpatrick

In the process of dismantling weapon pits from retired nuclear weapons, personnel at Los Alamos National Laboratory (LANL) have been receiving dose beyond their allowed limits. Using the Monte Carlo N Particle (MCNP6.2) code, models of the disassembly process were created to assess the effective dose rate a worker may receive and provide recommendations for procedural and shielding variations that could limit the effective dose on these workers. These models included different configurations of the generic plutonium weapon pit, variations of shielding arrangements and materials, and a simplified replication of a human torso for dose calculations. This work also provides a method to increase the fidelity of the radiation source terms by accounting for the ingrowth of daughter and decay products in these decades old materials via SCALE software. The results reveal a previously overlooked strong influence on the effective dose from neutron activity. Recommendations are then provided for procedural and shielding variations that could limit the effective dose on workers based on these new insights.

Pending availability at https://scholar.afit.edu/

Characterizing Variance in Fallout Composition Due to Uncertainty in Thermodynamic Models of Fractionation

MAJ James Gifford

This dissertation proposes a rapid, in-situ high resolution gamma spectroscopy technique to identify the fissile material and neutron spectrum of a nuclear explosive within hours of collecting fallout particles. The Defense Land Fallout Interpretive Code (DELFIC) was used to simulate a nuclear detonation in conjunction with the Korts and Norman thermodynamic model of fallout formation. This thermodynamic model has 400 input parameters, Henry's Law coefficients, and diffusion coefficients which have few, if any, measured values at extreme temperatures and unknown uncertainties. Using sensitivity analysis, the number of significant thermodynamic input parameters was reduced from 400 to less than 40. Applying active subspace decomposition, a reduced-order model with only 4 input dimensions was developed to replace the computationally expensive DELFIC calculations to enable direct sampling uncertainty propagation. A large range of assumed uncertainty for the significant thermodynamic parameters was employed to identify the uncertainty in the predictions of fallout composition. This work showed that it is possible to determine the fissile material and neutron spectrum of a nuclear explosive using multiples in fallout particles with thermodynamic coefficient uncertainties as large as ± 50% of their nominal values. This work also identified the significant thermodynamic parameters in fallout formation that must be measured with greater precision to reduce uncertainty in physical fallout models. The elements between arsenic and tellurium are the most influential thermodynamic properties for fallout formation and should be the focus of future thermodynamic coefficient measurements.

https://repository.lib.ncsu.edu/handle/1840.20/37334

Characterization of Transport Equations with Forensic Applications (Nuclear and Social)

LTC Nickolas Duncan

Convection and diffusion processes are used to understand transport in a wide range of contexts including the spread of diseases, the adoption of ideas within populations, and the classical applications to heat and mass transfer. While much attention is typically paid to formulating the appropriate equations to accurately capture the underlaying processes, the parameters that go into these mathematical models are equally important and receive far less attention. The SARS-CoV-2 emerged in late 2019 and caused a worldwide pandemic. Epidemiological models are playing a key role in guiding public health interventions. The SIR model (susceptible, infected, recovered) is used to predict the number of infections over time. Their ability to accurately predict the number of people who will become infected depends on input parameters that are poorly understood. Here the effects of uncertainty on predicted outcomes are explored. The diffusion of ideas on social media is also studied in this context. How ideas propagate can affect societal trends, norms, behaviors, influence markets and the outcomes of elections. The SIR model is again used, but here in combination with sentiment analysis to understand tweet behavior. Different sentiment messages spread at different rates through social media. Parameter estimation in the classical domain is conducted here to understand subsurface transport models that are used for post detonation nuclear forensics. Subsurface gas transport depends on accurately estimating the depth of the underground explosion as well as the geology that surrounds the explosion. The site of the explosions are likely to be denied access sites and parameter estimations must be done remotely. The depth at which a test occurs is known to be a critical parameter, affecting not only the migration time for gases to reach the surface but also their subsequent isotopic ratios. Bayesian data synthesis can improve depth of burst estimates by considering local topology, geology, the presence of surface deformation, yield, and a safety factor (for U.S. tests). Here a method is developed to characterize fracture width, spacing, tortuosity, permeability and porosity at a denied access site. Fractures are treated as fractals with their respective fractal dimensions determined using surface images. The input parameters were applied to a subsurface gas transport model for six underground nuclear explosions conducted by the Democratic People's Republic of Korea (DPRK).

https://mountainscholar.org/handle/11124/175337

Materials Science and Instrumental Techniques

Analysis of the Correlation Between Rhenium Filament Surface Features and TIMS Performance

MAJ Christopher Mihal

Thermal Ionization Mass Spectrometry (TIMS) is an invaluable tool in nuclear forensics as it enables isotopic assays of actinides to be measured, permitting analysis to include special nuclear material isotopic assays, nuclear reactor monitoring, and treaty verification. In one method of measurement for the TIMS system, samples are deposited in solution form on high-purity rhenium filaments. The filaments are heated to evaporate the solvent, and then further heated to cause sample ionization, permitting the sample to be transmitted through a magnetic field which separates ions based on mass to charge ratio into detectors for counting. Heavier ions will be deflected less by the magnetic field than lighter ions with equivalent charges. Critical to the function of TIMS is the rhenium filaments themselves; any variability that suppresses ionization of the samples can lead to reduction in the number of ions detected. This research examines twenty-four filaments utilized in TIMS for actinide analysis, with varying degrees of ionization efficiency. By examining the surface of the filaments using scanning electron microscopy (SEM), energy-dispersive x-ray spectroscopy (EDS), optical microscopy and electrical conductivity analysis, this research determined that there was no correlation between microscopic surface features and reported filament efficiency.

https://scholar.afit.edu/etd/3264/

Countering Proliferation: Carbon Fiber Characterization Through Nano-Mechanical Measurements with Peakforce QNM

MAJ Lorin Veigas

The purpose of this work is to develop a technique to quantitatively measure mechanical properties of microscopic samples of carbon fibers to determine the proliferation risk as a dual-use material. Measurements of the transverse elastic modulus of five types of carbon fiber were taken using PeakForce quantitative nano-mechanical mapping (QNM) atomic force microscopy (AFM). The transverse modulus was then compared to the longitudinal modulus of macroscopic fibers provided by the manufacturer to prove the inverse relationship that exists between the moduli. Demonstration of the inverse relationship between moduli enables the extrapolation from the mechanical properties of microscopic samples to the corresponding bulk material properties. Determination of the longitudinal modulus can then be used for determining if a given material is export controlled under International Atomic Energy Agency (IAEA) safeguards, thereby identifying potential proliferation concerns.

Error Reduction for the Determination of Transverse Moduli of Single-Strand Carbon Fibers via Atomic Force Microscopy

MAJ Joshua Frey
joshua.d.frey4.mil@mail.mil
joshua.frey@westpoint.edu

PeakForce Atomic Force Microscopy (AFM) Quantitative Nanomechanical Measurement (QNM) is utilized to measure the transverse fiber modulus of single strand carbon fibers to less than 5% error for 11 types of carbon fiber with longitudinal moduli between 924-231 GPa including export-controlled fibers. A positive linear correlation between the longitudinal and transverse modulus with an R2=0.76 is found. Statistical methods are employed to improve quality of data to exclude outlier measurement points in an image based on the peak force, adhesion force, and indentation depth. Statistical and physical criterion are also developed to exclude outlier images within the sample set. Three alternative methods for calculating the transverse modulus using the raw instrument data were also studied. These include approximation of the indentation force curve using the peak force and adhesion force values, approximation of the indentation force curve using the peak force and net force zero point, and a linear fitting of the measured indentation force curves at each indentation point. Pitch-based fibers are found to exhibit lower measurement error than polyacrylonitrile-based (PAN) fibers. Additionally, PAN fibers exhibited no apparent modulus correlation when the Pitch fibers are excluded. Underlying reasons for this lack of correlation are explored, with the most likely reasons being the difference in long-range order in the fiber microstructure and aging effects due to the different sourcing methods used to attain the PAN fibers.

Pending availability at https://scholar.afit.edu/

Development of a Magnetic Confinement Attachment for Signal Enhancement in Handheld Laser Induced Breakdown Spectroscopy (HH-LIBS) Soil Analysis

LTC Alfred Anderson

Field techniques for characterizing low levels of heavy elements of less than 100 parts per million in soils tend to be unreliable because of the relatively weak signal of these elements and the large, variable background inherent to analyzing soils with minimal sample preparation. To enhance the detection and analysis capability of a handheld laser-induced breakdown spectroscopy (LIBS) instrument, this work investigates the effects of a unique magnetic confinement apparatus on signal intensities, focusing on five iron lines as well as those from actinides in 11 soil samples. The proposed magnetic confinement apparatus achieved over 8 kG but did not amplify the elements' peak intensities of the samples equally. Some peak intensities decreased with magnetic confinement. The difference in the intensity is attributed to elemental composition of the soil samples. The peak intensity increases were attributed to increased plasma density under magnetic confinement, which increased the rate of recombination as the plasma cooled. The magnetic confinement apparatus was designed for use with the SciApsZ300 handheld LIBS but can be easily adaptable to other models. This novel approach provides a simple, field-expedient means of improving handheld LIBS performance.

Pending availability at https://scholar.afit.edu/

The Effect of Ferrofluid on a Dilatant Fluid's Intrusion Resistance

MAJ Joshua Strader

When small, macroscopic, solid particles (like glass beads or grains of starch) are immersed in Newtonian fluids (like water or glycerol), the resulting material demonstrates solidification under sudden driving, like from intrusion of an object above a threshold velocity. The physical means for this effect are not fully understood. One mechanism that has been proposed involves hydrodynamic pressure: the fluid must flow through the pore structure between particles as the material deforms. Consistent with this picture, the viscosity of the fluid has been identified as a contributing factor to this resistance. The ability to control the viscosity in real time would allow for maximum resistive pressure when needed and then for low resistance in between periods of high driving. One possibility for accomplishing this is using ferrofluids. Ferrofluids contain molecules of iron coated in a surfactant and suspended in a solvent. This mixture is capable of changing its viscosity when a magnetic field is present. I will explore the mechanical properties, including the impact resistance, where the simple Newtonian fluid is replaced with a ferrofluid. I compare this with existing data in literature and from previous projects in our group. I find that the experimental results match predicted theory to a point and then data suggests that other forces counteract these predictions. I find that ferrofluids are capable of creating a tunable complex fluid mixture and warrant further research.

https://calhoun.nps.edu/handle/10945/66725

Biological Sciences

The Effect of Aeration Rate and Free-Floating Carrier Media on the Emission of Bacillus Globigii in Bioaerosols: Kinetics and Spore Properties

MAJ Andrew Owens

Aerosols produced by turbulent mechanical mixing and bubble aeration at Waste Water Treatment Plants (WWTPs) become bioaerosols with the entrainment of biological materials. Bioaerosols become a public health risk when human pathogens are present. This study evaluated bioaerosols containing Bacillus globigii (BG) spores and the effects that aeration rate and the addition of Free-Floating Carrier Media (FFCM) had on the amount of BG collected following aerosolization. A series of laboratory-scale experiments investigated two different sizes of floating polystyrene spheres as FFCM and four different aeration rates. A relatively weak correlation was reported between increasing the aeration rate from 0.50 to 1.00 L/min, although the overall percent change of BG spores captured increased between 97.58% and 352.60%. The addition of FFCM of both sizes reduced the amount of BG spores captured when compared to the control. Smaller spheres (0.42 cm diameter) consistently attenuated BG bioaerosol emissions more effectively than those with larger (1.91 cm) diameters, with a mean control efficiency of 93.03% compared to 83.95%. Statistical analysis showed a significant increase in the ability of smaller diameter FFCM to attenuate bioaerosol production at the two higher investigated aeration rates. This study was the first, to the author's knowledge, to investigate multiple effects on bioaerosol production where the aerosol contained strictly bacterial endospores. As a part of a larger investigation including laboratory scale and pilot-scale WWTP research, this study is the first in a series of studies intended to investigate the effect of experimental scale on bioaerosol production. Results related to effects due to scale can be applied to better predict bioaerosol behaviors in operating treatment plants.

https://scholar.afit.edu/etd/3266/

Characterizing the Porcine Adaptive Immune Response to Homologous/Heterologous Porcine Reproductive and Respiratory Syndrome Virus Type 2 (PRRSV-2) Strains

LTC Andrew R. Kick
andrew.kick@westpoint.edu
andrew.r.kick.mil@mail.mil

Porcine Reproductive and Respiratory Syndrome Virus (PRRSV) is the prevailing disease affecting the US pork industry. In Chapter 1, we propose testable immune correlates of protection for PRRSV research. In Chapters 2 through 4, we characterize the adaptive immune response (T cell and humoral) to homologous and heterologous PRRSV strains. Within PRRSV research, we provide the most in-depth analysis to date for the specific T-cell response to homologous and heterologous PRRSV strains as well as characterization of the development of neutralizing antibodies against different PRRSV strains in young pigs and those transferred through maternally-derived immunity. The main conclusion: The T cell response to PRRSV is cross-reactive across PRRSV strains enabling broader protection while the humoral immune response (neutralizing antibodies) tends to be strain specific and exhibits less cross-reactivity between strains. In Chapter 5, using Joint Publication (JP) 3-0, we describe the phasing of operations and the risk at operational transitions and apply this conceptual model to the PRRSV immune response in order to pose future immunology research questions. Collectively, this dissertation provides novel and foundational discoveries of the adaptive immune response to PRRSV and generates numerous research questions for the future.

https://repository.lib.ncsu.edu/bitstream/handle/1840.20/37326/etd.pdf?sequence=1

Other Publications

The T-Cell Response to Type 2 Porcine Reproductive and Respiratory Syndrome Virus (PRRSV)

https://www.mdpi.com/1999-4915/11/9/796

Maternal Autogenous Inactivated Virus Vaccination Boosts Immunity to PRRSV in Piglets

https://www.mdpi.com/2076-393X/9/2/106

Policy Studies

Deterrence in the Danger Zone: How the United States Can Deter Russian Gray Zone Conflict

MAJ Whitney L Cissell
whitney.cissell@usspacecom.mil
whitney.l.cissell.mil@mail.mil

In recent years, adversaries of the United States have become increasingly more adept at operating in the gray zone, which sits above normal statecraft and below armed conflict. In 2016, Russia used cyber-espionage and covert influence operations to sow discord among the American population and interfere in the democratic process of the U.S. presidential election. This attempt was but one part of a broader Russian gray zone strategy in which it uses non-military means to achieve its national objectives and gain influence while avoiding a powerful response from either the United States or NATO. In this sphere, non-democratic adversaries of the United States are at an advantage as they are often more agile and expeditious at integrating all elements of state power, especially economic power and informational warfare. This thesis draws on interviews with subject matter experts to explore how the United States can best deter these gray zone actions and strategies in the future. In doing so, it provides a strategic assessment of Russia as a state actor, U.S.–Russian relations, and Russia's use of the gray zone. Additionally, it analyzes the transposition of deterrence to the sub-conventional level. Finally, it illustrates ways in which the United States can deter parts of Russia's gray zone strategy. Overall, this research finds that it is difficult but possible to deter Russian gray zone conflict.

http://hdl.handle.net/10945/64844

A Tale of Two Treaties: The Rise and Fall of Nonproliferation Agreements in North Korea and Iran

MAJ Alex Landrum
alexander.k.landrum.mil@mail.mil

Since the first use of nuclear weapons in the second World War, preventing their subsequent proliferation and use became among the gravest pursuits of international foreign policy. At the same time, states like Iran and North Korea, on the fringes of the international community, pursue acquisition of nuclear weapons based on diverse sets of individual objectives and motivations. To stave off these aspirations and shore up the nonproliferation regime, the United States endeavored to establish negotiated arrangements, first in 1994 with the Agreed Framework with North Korea, and later in 2015 with the Joint Comprehensive Plan of Action (JCPOA) with Iran. Both agreements followed an intensive exchange of negotiations that arrived at optimistic and amicable solutions yet were ultimately unable to secure their long-term nonproliferation objectives. The failure of the Agreed Framework to prevent the nuclearization of North Korea establishes an alarming precedent as the JCPOA appears to follow an analogous arc in the same direction. The implications of the examples of the Agreed Framework and JCPOA highlight the diminishing utility of negotiated settlements that fail to fully account for the realist dynamics that underpin nuclear proliferation.

Capstone research paper available directly from author.

Other Publications

Why Can't We Be Friends?: An Assessment of U.S.-Russia Relations and Deterrence
https://www.nec.belvoir.army.mil/usanca/CWMDJournal/CWMD%20Journal%20No20.pdf

How to Submit an Article to the *Countering WMD Journal*

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U.S. ARMY NUCLEAR AND CWMD AGENCY

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