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About the cover: Ivy-Mike Thermonuclear test shot, November 1, 1952 (courtesy of LANL Archives), is surrounded by U.S. Department of Defense Nuclear delivery platforms and warfighters.

Inside the Journal

Director Notes

COL Benjamin Miller
Director, USANCA

This year has already proven to be of major importance to us in the nuclear and CWMD community. Many efforts across the government and the Department of Defense (DoD) are shaping the future direction of our nation and its capabilities. Earlier this year, the President directed DoD to undergo a new Nuclear Posture Review (NPR). The team was formed from across the government agencies and departments where they work to provide the President with a new NPR aligned with his goals and national objectives. USANCA, representing the Army, participates in these discussions and assists in answering questions and debates surrounding nuclear weapons, their role, their use, and ensuring the Army's equities are being addressed as the team develops this critical policy document. This important work will continue into 2022 when we should see its publication sometime after the new year.

In November the Secretary of Defense directed the DoD to undertake the first comprehensive Biodefense Posture Review (BPR). The objective of this review is to posture the Department to prepare for and respond to the full spectrum of biological threats, whether naturally occurring, accidental, or from a deliberate attack. The BPR is underway and USANCA is the Army lead for this effort; providing the Army's collective input on biological defense in the following areas: 1) strategy, policy, & partnerships, 2) capability and capacity, 3) total force readiness, and 4) industrial base and supply chain. The BPR will also continue into next year with a final report expected in 2022.

In CWMD Readiness some major efforts are being pushed by the US European Command (EUCOM) as they finish writing their CWMD Implementation plan (Iplan). This Iplan was developed with assistance from both the US Special Operations Command (USSOCOM) and USANCA as it responds to the final 2020 Office of the Secretary of Defense CWMD/CBRN defense readiness assessment and subsequent USSOCOM Senior Leader Seminar. The Iplan provides EUCOM with a way ahead to increase their knowledge base, planning, and capability to conduct CWMD operations. As the demand from Geographic Combatant Commands (GCC) increase for this expertise, our role within the CWMD community becomes even more essential to provide our leaders with options and associated risks as they make decisions.

Not only are we assisting the GCCs as they look at CWMD, we also are working through the Army Campaign plan for the modernization of CWMD readiness to shape the future force. USANCA is spearheading an effort to provide a proof of concept to Army leadership that would take a Brigade Combat Team through a life-cycle training timeline and result in a trained and ready formation to plan, operate, and win in a WMD environment. This messages one of the Army's major roles in deterrence for national security - demonstrating we can operate in any environment under any condition, with minimal effect to our force.

Along with our efforts through the Army Campaign Plan and Objective 7, Modernize Conventional-Nuclear Integration, CWMD Readiness, and Biological Defense; our team at USANCA was successful in obtaining resources to implement the Army Biological Defense Strategy through its Army Biodefense Office of Primary Responsibility. We continue to work with GCCs, ASCC, and DoD to refine and ensure our future force is ready and capable to operate in this unique environment.

The CWMD Advisor Course continues to train and educate staff members on specific training at the operational and strategic level addressing a shortfall identified by DoD. Our instructors and administrators are working with many commands to provide this course and are looking into mobile training team options for future editions. This course provides Army personnel with the D1 skill identifier and is open to all DoD personnel. The Theater Nuclear Operations Course and Seminar also support theater staffs and provide training that focus on nuclear threats and the planning at the operational level for nuclear use. The USANCA team of instructors continues to support GCCs, Theater Commands, FCCs, and ASCCs along with working on new curriculum for future efforts across the Army.

All these actions are in concert with what is being spearheaded with our Allies and Partners. Earlier this fall, USANCA sent our U.S. Head of Delegation to the first "in-person" NATO Joint Chemical, Biological, Radiological and Nuclear Defense Capability Development Group (NATO CDG) meeting since the start of the pandemic. The meeting included 60 delegates from 19 NATO and 6 partner nations. The NATO CDG received higher level guidance from the tasking authorities and updates on the status/issues of the standardization work executed by its seven subordinate panels. The U.S. offered to assist NATO in development of a solution for CBRN Functional Service – a C2 capability package for the NATO Command Structure.

The FA52 Nuclear and CWMD Officer Proponent and USANCA continues to foster a diverse and inclusive community of FA52 professionals. Specific goals of the FA52 Diversity Program are to increase the percentage of female and minority FA52 officers over a five-year period to meet or exceed the Army officer demographic and to increase the number of FA52 officers from basic branches not typically associated with FA52. Most recently, the FA52 Proponent established the Diversity and Inclusion Working Group (DIWG) to enhance the education, outreach, and recruiting required for a more diverse FA52 officer corps.

USANCA is working to support you, the CWMD community, and provide the expertise for planning and operations, testing, policy, doctrine, effects analysis, and support for CWMD requirements. We appreciate your thoughts and ideas. Let us know how to better support you or improve the CWMD Journal.

Keeping Me Awake at Night:
The Coming Nuclear and WMD Battlefield and the Urgency to Improve Army Readiness

MG Bradley Gericke PhD, MAJ Thomas Halverson,
Mr. Stephen Carey, LTC Jason Wood

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

In war, land power ends campaigns. Warfare in the sea and air domains, now integrated with those of cyber, space, and the electronic spectrum, enable ground forces to bring overwhelming combat power to bear in new ways to terminate the theater fight. History bears out the primacy of land power – in every major conflict across the spectrum of conflict from OVERLORD to DESERT STORM to IRAQI FREEDOM. U.S.-led coalition forces, when allowed to mobilize, deploy, and position themselves at will, have triumphed. Our adversaries have watched this template play out time and again. We must assume that they have learned the lesson and will not permit the United States or our partners to mobilize and deploy on extended timelines again. They have innovated to deny dominance of any U.S.-led coalition force in a set-piece theater fight. Their operational response will now almost certainly include novel approaches to employing weapons of mass destruction (WMD) to terminate a theater fight on their terms or prevent the United States from fighting it altogether.

Major General Gericke assumed responsibilities as the Director for Strategy, Plans, and Policy within the U.S. Army's G-3/5/7 during July 2019. As the Army's senior strategist, MG Gericke not only provides strategic assessment and advice to the Chief of Staff and other Army senior leaders, he also oversees the training, education, and development of all the Army's strategists (Functional Area 59). In his prior assignment, MG Gericke served as the Deputy Director for Joint Strategic Planning in the Joint Staff J-5. He received a BS in modern historical studies (Europe) from the United States Military Academy and an MA and Ph.D. from Vanderbilt University. He also graduated with a MMAS in Strategy from the United States Army Command and General Staff College and an MS in National Security Strategy from National Defense University.

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This is not to rule out that our adversaries include in their planning the capability to wage war through the intercontinental exchange of strategic nuclear weapons as in the infamous Mutually Assured Destruction nightmare. Rather, it is difficult to imagine a scenario in which a WMD-armed adversary would not employ a WMD capability at echelon, not just in extremis, but to avoid extremis in the first place when faced with a U.S.-led coalition. Nuclear weapons are an obvious choice, but viable scenarios also include the employment of chemical weapons to interrupt U.S. force employment, or the un-attributable release of a biological pathogens to sow international discord.

In 1991 the Iraqi government opted not to employ chemical weapons in the face of an offensive campaign conducted against them by an overwhelming U.S.-led coalition. At the time, U.S. commanders were “baffled” by this decision.[1] Following his capture, interviews with Iraqi President Saddam Hussein revealed that he held the Iraqi chemical weapons arsenal in reserve as a deterrent against the United States or Israeli WMD use.[2] Whatever the motivation in 1991, by the time the Iraqi regime was destroyed by another U.S.-led coalition in 2003, one lesson emerged from Saddam’s choice – WMD could provide a means to deny a coalition the time needed to build combat power, and possibly end a limited conflict on beneficial terms. If this lesson is learned, our adversaries will have concluded that employing WMD improves their chances of winning a theater conflict. Given this recent history, it remains to assess if adversary modernization suggests WMD are a key capability.

Nuclear weapons remain relevant to the modern strategy of the United States and its near-peer adversaries who continue to modernize their nuclear arsenals. And while the United States employs only those delivery systems governed under the New START and in support of NATO, our adversaries continue to develop and field a diverse array of short and intermediate range delivery systems capable of employing nuclear and conventional payloads (so-called “dual-capable” systems[3]). This complicates “strategic calculus” by adding a custom-made nuclear capability for theater use that is practically impossible to separate from conventional arms posing urgent operational challenges to the Army and U.S. coalition forces.

Like the development of dual-capable weapon systems, innovations in chemical weapons development and employment has the potential to provide asymmetric capabilities against a dominant coalition force in a theater context. Russia has likely employed covert fourth-generation agents (FGA) in targeted attacks within the U.S. European Command area of responsibility.[4] In one example, the 2018 assassination attempt that targeted Sergei Skripal employed FGA.[5] While unsuccessful, it killed one person unassociated with the attack and required a clean-up effort that involved more than 600 personnel, cost more than $30M, and took more than one year to complete.[6,7] These chemical warfare agents, with low volatility and late onset of symptoms, pose unique detection challenges that could be used to disrupt force projection and both strategic and operational maneuver. It does not take an active imagination to recognize the utility of their use.

Russian forces have fielded pharmaceutical-based agents, demonstrating a capability to quickly and effectively neutralize unprotected personnel. In 2002 Russian forces employed a fentanyl-derived incapacitating agent in a counterterrorist hostage situation, killing all 40 terrorists and 130 of the 800 hostages.[8] Again, it is not difficult to see how an adversary could leverage such a capability to impede the ability of a U.S.-led Joint Force to mobilize, deploy, and array forces.

In more recent memory, the COVID pandemic brought significant consequences to the U.S. Army (and the rest of the DoD). Individual and collective training was put on hold or modified, multinational exercises were cancelled or moved into a virtual setting, and the might of the defense establishment turned its energies to mitigating the impact of a naturally-occurring virus.[9] Across the world our partners and adversaries alike were required to adapt. While the impacts of a future pandemic, engineered or naturally-occurring, would certainly be felt globally, it is not difficult to see the potential for weaponized biological agents to prevent the United States and its Allies from bringing the might of a coalition force to bear in a theater fight.

So, what can the Army do? Much can be done is the answer. Army forces enable the Joint Force to terminate the theater fight not by employing WMD, but by maneuvering over the ground to destroy the enemy, seize and hold terrain, and mitigate the consequences of WMD employment by the enemy. As the Army orients on the future and its ability to achieve dominance in a multi-domain fight, it must ensure that it modernizes forces and systems to meet emerging WMD challenges in order to terminate the theater fight. The Army recognizes our critical role in deterring adversaries and the possibility of theater WMD use. As part of Headquarters, Department of the Army G-3/5/7, the U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency (USANCA) leads Army efforts to deter WMD use among our competitors and potential adversaries.

Institutional change begins with strategy. Central to related modernization efforts are a Conventional-Nuclear Integration (CNI) Strategy, a new Biological Defense Strategy, and an effort to re-prioritize CBRN defense and survivability at all echelons. These efforts are driving change in several areas that will show a lasting impact on our Soldiers and Army readiness. As with all Army missions – doctrine, education, training, exercises and planning are key components in building this readiness. Fluency and understanding of WMD effects, adversary capabilities, and U.S. employment of nuclear weapons must be prioritized or added to our leader development across the Total Army. These efforts continue to bring key WMD concepts into our operational planning as an Army and Joint Force. WMD-focused training and exercises at the theater strategic, operational and tactical levels will ensure commanders and soldiers understand their role and the risks of conducting operations in a CBRN environment.

In April of 2021, the Army published the Army Biological Defense Strategy, which provides direction for the Army as it looks at biological weapons and guides the synchronization of Department of Defense and Army equities. Following its success, USANCA is leading development of the Army CNI Strategy, Countering Weapons of Mass Destruction (CWMD) Strategy, and Survivability Strategy. The CNI Strategy will give direction on the integration of nuclear considerations into Army processes and missions driving new or refined approaches in support of strategic objectives across the spectrum of conflict – competition, crisis, and conflict. The Army, as part of the Joint Force, will be able to secure national and theater objectives against a nuclear-armed adversary in support of the U.S. strategic deterrent, and in the event deterrence fails, ensure Army lethality. The CWMD Strategy and Survivability Strategy, when published, will provide clarity on the multi-domain Army's roles, responsibilities, and capabilities as applied as applied to operations to counter and survive WMD threats.

All of these strategies will help focus efforts and ways to assist the Army, DoD, and other government partners in meeting strategic objectives. Producing strategies takes time and effort to address the equities held by the many stakeholders. Far more challenging than developing strategies, however, is implementing them in this era of scarce resources. In a budget-constrained environment, the Army must ensure that modernization efforts address innovations in adversary theater-focused WMD capabilities while producing the multi-domain Army.

The Army is improving its ability to fight on the nuclear battlefield. In April 2020, the Joint Staff released Joint Publication 3-72 Nuclear Operations, which establishes a common lexicon for joint operations and reintroduces considerations of nuclear warfighting in a contemporary context. Nested with this document, TRADOC is preparing to publish *ATP 3-72 Multi-Service Tactics, Techniques and Procedures for Operations in a Nuclear Environment,* which provides a basis for tactical commanders and staffs to plan for the impact of nuclear effects on the battlefield – a skill long atrophied following the fall of the Soviet Union that seemingly removed our impetus for nuclear competition, and the attacks of September 11, 2001 that drove the nation to refocus on counter-terrorism. Translating this emerging doctrine into understanding at the senior leader level, the Theater Nuclear Operations Executive Seminar (TNOES) facilitates discussion of theater integration of U.S. nuclear capabilities into conventional operations including planning, targeting concepts, nuclear weapon effects, and the impact of nuclear employment on the scheme of maneuver. The success of TNOES has generated follow-on Army actions to develop a curriculum to integrate nuclear operations into PME at all echelons.

In addition to TNOES, The Army offers two theater-level courses that help educate the force in both nuclear and CWMD operations. The Theater Nuclear Operations Course (TNOC) educates theater-level staff officers to plan for joint nuclear operations and targeting, and provides instruction on impacts to conventional operations during U.S. nuclear employment. Separately, the CWMD Advisor Course provides students with the analytical tools needed to solve problems posed by WMD, CBRN materials, and dual-use materials. Successful graduates earn a D1 skill identifier and use the knowledge gained to advise Combatant Commanders and staffs. These courses are only the beginning.

With the emergence of the Multi-Domain Operations (MDO) concept and the return to great power competition, TRADOC's Combined Arms Center (CAC) has updated the instruction given to Captains to include MDO to ensure they are ready to meet the challenges posed by changing environments today and in the future. USANCA has begun work with the CAC to update the Captain's Career Course curriculum to address nuclear operations and CWMD and is developing options for other Professional Military Education at every echelon. This inclusion will pay dividends in the future by reducing the vulnerabilities our formations face from theater employment of WMD, ensuring the MDO-ready force can fight, survive, and win on any battlefield.

As the Army refines its own doctrine, training, and education to address the theater risks posed by WMD, we also support the Joint Force directly through assistance to Combatant Commands. In 2021 the Army took a leading role in helping USEUCOM write, coordinate, and publish a CWMD and CBRN implementation plan that will enable theater forces to overcome gaps identified during a 2019 OSD assessment. Key to success will be revised theater entry guidance that requires rotational units to integrate WMD challenges specific to the European theater into their pre-deployment training and validation activities. Following the success of this effort, Army WMD experts will support USINDOPACOM in assessing land component readiness to overcome legacy and future WMD threats from actors across the Pacific Theater.

To demonstrate the deterrent potential for ground forces at all echelons, the Army is conducting a proof-of-concept in 2023 and 2024 that will demonstrate improved capabilities at echelon from Land-Component Command to BCT to conduct large scale combat operations against a near-peer, WMD-capable adversary. The 2023 effort is well into the planning phase and will focus primarily on overcoming Russian WMD threats in the European theater. Initial planning is underway to follow this European-focused pilot with a second effort in 2024 that demonstrates the capability of Army formations to achieve multi-domain dominance in the face of Pacific-theater WMD threats.

These Army-wide efforts driven by HQDA G-3/5/7 will help ensure that our adversaries will not turn to WMD to seek advantage. By demonstrating the will and ability of U.S. ground forces to overcome the challenges of WMD effects at the ASCC, Corps, Division, and BCT levels, the Army can impose one of the most potent deterrents on our adversaries—the doubt that WMD will succeed in terminating a theater conflict on beneficial terms. Success, though, depends on adapting and changing priorities at all echelons of the Army. This will require re-prioritization of WMD-focused training at every level of command, increased funding, and, the most important investment of all, time to educate and train our soldiers to overcome this threat. Successfully adapting our priorities and resources to address WMD threats will enable our divisions to converge and dominate across all domains, and, where possible, end campaigns before they begin. If we fail to adapt, however, the risk to our formations will increase as our adversaries continue to innovate, further reducing the ability of our ground forces to overcome WMD threats to get into position, let alone win the fight.

It is imperative we develop, educate, train, and exercise with our Allies and Partners to bring them with us in this pursuit of more effective deterrence. The United States and our partners must compete and campaign aggressively today as we build readiness for tomorrow's contingences that, if they come, will always involve the threat of WMD, and logically could witness WMD employment. The more our Army and Joint force is capable of operating, fighting, and winning on the WMD battlefield the more we can secure the peace and win the first campaign of the next war.

We can be sure that in the future, as in the past, land power will terminate war.
We Must Be Ready.

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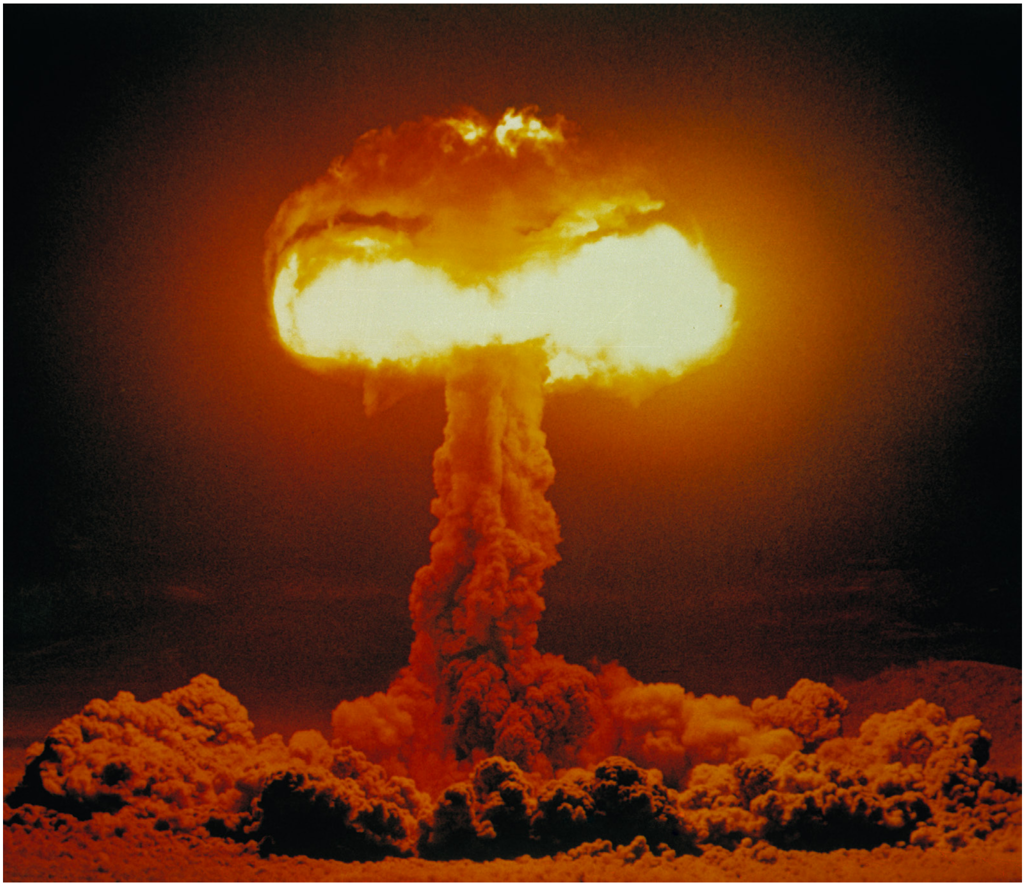

Plumbob-Hood test shot, 5 July 1957, (LANL Archives)

Metamaterial Technology for the Advancement of Proliferation Detection

Christine Brockman, Minority Educational Institution Student Partnership Program (MEISPP) Intern

Department of Energy, National Nuclear Security Administration (NNSA)

Research sponsored by the Office of Defense Nuclear Nonproliferation Research & Development (DNN R&D) Office of Proliferation Detection to further advance nuclear proliferation detection technologies is constantly advancing. These technologies include the development of materials and processes that are applicable to support a variety of detection activities. "Materials by design" is an effort that is included in this technological advancement; it encompasses the design and manufacture of materials, processes, and complex systems for improved proliferation detection. These concepts may include artificial intelligence and machine learning-aided design, the progression of advanced manufacturing, and the development of metamaterials with new advantageous properties.

Metamaterials can be defined as materials that derive their response from patterned structure. These materials are engineered and designed to have properties that are not found in their naturally occurring state. Further, metamaterials are designed using a combination of multiple elements arranged in repeating patterns, at one or multiple scales, that need to be smaller than the typical wavelength they aim to control.[1] The designed arrangement, shape, or orientation allows for properties capable of manipulating electromagnetic waves to achieve new benefits that are not present with conventional materials. Research and development of metamaterials has broad applications within research relevant to proliferation detection missions, including the enhancement of optical, radiation, and infrasound detectors. In particular, metamaterials may enable the reduction of size, weight, and power of such systems and could improve overall sensitivity and specificity.

A metamaterial's metasurface (the planar analog of a metamaterial) response can be customized for a specific application through the microscopic design of the material layout. A basic example of this is a split ring resonator, a structure that is a ring at subwavelength dimensions with a segment removed from one side. As shown in Figure 1., this ring acts as an RLC circuit, with a resonance frequency determined by its inductance and capacitance; the inductance and capacitance are in turn determined by the ring geometry.[2] The variables shown in Figure 1 are used to calculate the resonance frequency of the split ring. rav represents the average radius of the external split ring resonator, d is the distance between the two resonators, and c represents the ring thickness. The response of the split ring can then be modified by changing the dimensions of the ring. This describes the principal concept of customizing and tuning a material in an effort to improve device performance. Both 2-D and 3-D additive manufacturing techniques enable the rapid design and development of metamaterials.

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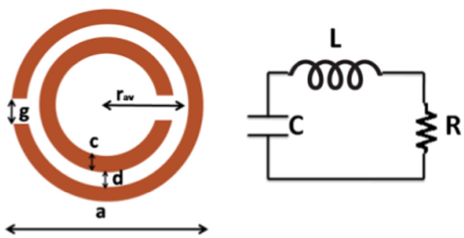

Figure 1. Schematic of a double-turn split-ring resonator and equivalent RLC tank circuit of a single split-ring resonator.[2]

There are several areas where metamaterials have the potential to significantly impact proliferation detection missions. For example, metamaterial- and metasurface-based lenses and color correctors can be used to replace lenses within an optical system, enabling new functionality. Conventional refractive optical systems rely on the combination of several, difficult to fabricate lenses. They are generally bulky, costly, and time-consuming to manufacture with high precision. However, "metalenses" based on metasurfaces have been examined for the creation of achromatic optical elements. Their surfaces control phase delay as a function of location, which is enabled via position-dependent lithographic patterning of a planar structure.[3] Illustrated in Figure 2, metalenses can be engineered with tailored dispersion for desired achromatic focusing. To realize this, the phase profile must satisfy an equation that accounts for angular frequency, light speed, radial coordinate, and focal length.[4] Conventional diffractive lenses only satisfy the phase at the design frequency, leading to chromatic effects. However, with the use of engineered metalenses, it is possible to control the phase, resulting in an achromatic focusing. Additionally, these materials provide the advantage of weight reduction when compared to conventional optics, as their design is thin. These optical components show potential for modification and improvement of proliferation detection optical systems.

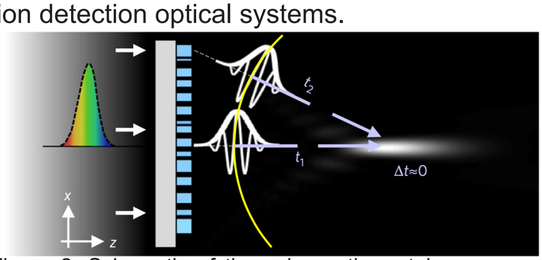

Figure 2. Schematic of the achromatic metalens concept. The metalens is designed to provide spatially dependent group delays such that wavepackets from different locations arrive simultaneously at the focus. t_1 and t_2 represent complex transmission coefficients for each wavepacket. The yellow line represents the spherical wavefront.[3]

Recent studies have also demonstrated that metamaterials facilitate improved functionality for scintillators, a core, background technology for radiation detection. They provide a comparably low-cost method to identify the presence of radiation. Scintillators convert high-energy radiation to a near-visible or visible light. This is achieved via radioluminescence, a method for producing an isotropic burst of low-energy photons. A portion of this light then travels through the scintillator crystal and is subsequently analyzed as an electrical signal produced by the photodetector.[4] In modern designs, this photodetector is typically a silicon photomultiplier. Scintillators are also commonly used in medical imaging, specifically Positron Emission Tomography (PET), where thousands of scintillator detectors are arranged to record correlation pairs generated by absorbed biologically active radioisotopes.[5] However, scintillators sometimes lack the capability to differentiate between types of radiation, identify the location of the radiation source, or precisely measure the emission energy spectrum of that source. With the use of metamaterials, scintillator performance can be improved. Specifically, metasurface cladding on the exterior of a scintillator can prevent signal loss by reducing the transmission of light out of the scintillator, which results in an improvement in signal and timing resolution. Improving timing resolution can lead to enhanced signal discrimination. A reduction in time resolution would also lead to fewer random events being recorded, leading to an improvement in the signal-to-noise ratio.[6] By control of the shape, size, and relative location of each structure within the reflection metasurface, the relative phase introduced by induced dipoles to incident light can be controlled. Metamaterial enhanced detection may also provide a method to enable improved detector efficiency by controlling detector bandwidth or improving detector response through resonant interaction. Metasurfaces have also allowed for the customization of spectroscopy systems, as they have been used for entirely solid-state miniaturized spectrometers where the dispersive element is integrated monolithically with the detector.[7]

Currently, a developing research project sponsored by the Defense Nuclear Nonproliferation R&D Office of Proliferation Detection focuses on the design of a neutron detector that uses an anisotropic scintillator metamaterial (ASMM).[8] Figure 3 shows a graphic of the detector design. Neutrons are a signature of the presence of special nuclear material (SNM). This detector will integrate the metamaterial scintillator into a fully functioning detector that will locate and characterize SNM. Existing instruments, such as thermal neutron detectors, can identify the presence of neutrons, but limitations occur with the ability to locate sources or measure the neutron spectrum to characterize sources. This ASMM neutron detector can identify the presence of SNM, point to the location of the material, and characterize the composition using spectroscopy.[8] These capabilities align with nonproliferation missions, as this technology will help monitor SNM under safeguards or treaty verification, as well as in emergency scenarios. In safeguards or treaty verification, identifying the location of SNM or using spectroscopy to characterize SNM can prevent tampering or spoofing. Recognizing the source location can also reduce backgrounds in interrogation measurements. This ongoing technological development is an improved alternative to existing neutron detection technologies while offering lower cost and complexity.

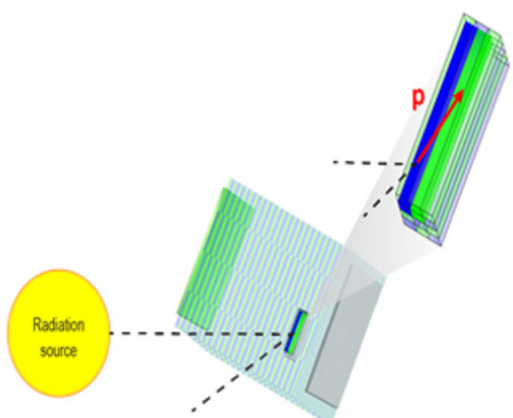

Figure 3. ASMM neutron detector design. Composed of alternating microscopic zones (50x50x50 microns) of scintillators small enough to give the detector sensitivity to the angle between a neutron-induced proton recoil and the long axis or “grain” of the zones. (J. Brodsky, 2020. Used with permission)

Another group of metamaterials, aside from those for optical and electromagnetic applications, is acoustic metamaterials. Acoustic metamaterials are of interest in the context of proliferation detection due to the ability to control and detect infrasound waves and vibrations through a range of frequencies. Natural infrasound can travel far distances, making it an invaluable resource for monitoring seismic phenomena such as nuclear explosions, volcanic eruptions, and severe storms.[9] In infrasound detection, sensors can be employed for the detection of nuclear explosions.[10] Typically, pressure sensors are used to capture waves, but they cannot encode the direction of arrival. This information is critical when the source location is unknown beforehand. Capturing this information would require the implementation of sensors with apertures ranging from tens of meters to kilometers depending on the wavelengths of interest. This can be impractical in many cases, depending on locations that may lack the space. With a sensor based on acoustic metamaterials, a much smaller footprint can be achieved, expanding the locations where the sensor can be deployed. Metamaterial-based sensors use arrays of sensitive microbarometers to identify the location of infrasound sources and detect the direction of arrival. Metamaterials also offer additional possibilities in wave control because infrasound frequencies are very low with correspondingly large wavelengths. For this application, sub-wavelength control is essential to having devices of a practical size.[9] These concepts have only recently been extended to infrasound, and further research continues to investigate the applicability.

Metamaterials currently have the potential to immediately impact NNSA missions and national security. This area of materials development has progressed to many applications. Metasurfaces can be designed to modify signals, optical modeling software developed for metamaterial design has shown potential for signal inversion, and metamaterials have made it increasingly possible to obtain details of a hidden target when compared to using optical probes alone. Extensive work performed at U.S. National Laboratories has explored the applicability of metamaterials; there exists the ability of metamaterials to enhance development within proliferation detection, and they can be realized in technology through further research and implementation.

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The Fate of the USS Arkansas (BB-33) in Crossroads Baker

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Summary

Using the extensive data that was recorded during Operation Crossroads in 1946, staff at Los Alamos National Laboratory (LANL) conducted an analysis to determine the fate of the USS Arkansas during test Baker. The recorded data are checked with a basic physics calculation and a calculation using a modern hydrodynamic physics code. These methods help to understand and validate that the USS Arkansas was not lifted vertically stern-high into the water column, in contrast to the myth based on the photograph showing a mysterious dark streak in the water column, long thought to be the Arkansas.

Operation Crossroads

Operation Crossroads had its origins before the first atomic bomb test was executed in the New Mexico desert in 1945. Operation Crossroads started as a rare collaboration between the Chiefs of the Bureau of Ships and the Bureau of Ordinance (Department of the Navy) which both decided that as the second world war was ending in the European theater, and the Pacific campaign was reaching its climax, that the best way to disposition the many ships held by the United States (including captured vessels) was to conduct full-scale explosive tests to obtain data on survivability of naval vessels in wartime. The intent was to substantially expand the data and understanding from small-scale explosive tests already conducted, leading to better ship design in the future [1].

This planning for full-scale destructive testing of naval vessels took on a different perspective after the Trinity test on 16 July 1945, the first ever atomic device detonation. Only three weeks after this momentous and successful test, the first atomic bomb used in combat was dropped on Hiroshima, Japan. Following the second atomic bomb dropped at Nagasaki on 9 August 1945, and the unconditional surrender of Japan on 14 August 1945, the war was officially ended.

"On 1 October 1945, Vice Admiral Cochrane and Vice Admiral Hussey sent another letter to the Chief of Naval Operations stating that the appearance of the atomic bomb 'has made it imperative

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that a program of full-scale testing be undertaken to determine the effects of this type of bomb, both underwater and above water, against ships of various types'"[1].

Following presidential approval, the Joint Chiefs created Task Force One on 11 January 1946, commanded by Vice Admiral W. H. P. Blandy. Vice Admiral Blandy chose the Bikini Atoll in the western Pacific due to its remote location, the infrastructure there and in the surrounding islands left after World War II and its ease of use for this type of testing.

Crossroads Able

The first experimental test of an air-dropped atomic weapon, and only the second full scale atomic test in history, Operation Crossroads, shot Able (Figure 1) served many purposes. The first was evaluating the effects of this type of weapon on ships of various types, classes, and orientations in the target array. The second was training for bomber crews in atomic weapons handling and delivery. The third was creating a collaboration between the Navy, the Army Air Corps, and the newly named Los Alamos Scientific Laboratory in conducting large-scale nuclear weapon experiments.

This test was conducted on 30 June 1946, with a Mark 3 "Fat Man"-style implosion device nicknamed "Gilda" dropped from the specially modified B-29 "Dave's Dream" and detonated 523 ft above the target array of ships. The blast was equivalent to approximately 21 kilotons of TNT [2]. The bomb missed the intended mark (USS Nevada) by approximately 615 yards to the west-northwest, detonating 50 yards from the USS Gilliam (APA-57) [3].

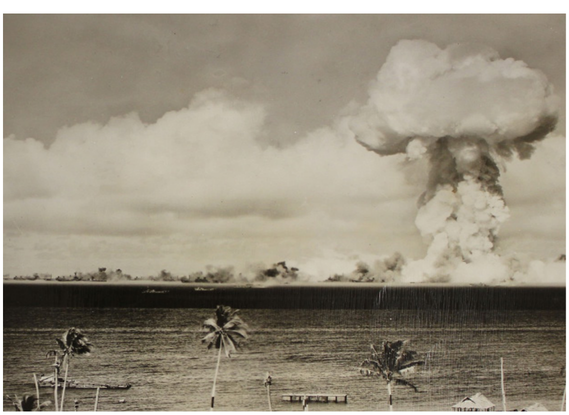

Figure 1, Crossroads Able Test Photo, (LANL Archives)

The USS Arkansas, situated approximately 620 yds from the actual zero point, suffered substantial damage from test Able. There was considerable damage to the starboard side and stern superstructure. The blast hit at an apparent 120-degree angle from the bow and about 30 degrees up from water level. The deck plating in the stern area was buckled and dished, particularly on the starboard side, where the blast originated from. This blast also heavily damaged the boiler stack indicating heavy air shock to the entire ship. The boilers inside were heavily damaged, which would have significantly impaired the ship's mobility [4]. This blast likely dislodged any caked-on stack soot that would have been packed in the exhaust stack and allowed it to be in a loose, powdered form that could easily become lofted from a subsequent transverse shock.

Crossroads Baker

Figure 2., Crossroads Baker Test Photo (LANL Archives)

The underwater nuclear test named Crossroads Baker (Figure 2) was conducted on 25 July 1946 to study the effects of an underwater nuclear blast on ships of various classes and orientations to the blast. This test was also conducted with a Mark 3 "Fat Man"-style implosion device moored 90 ft underwater at a depth of 180 ft from surface to ocean bottom. This blast produced the equivalent explosive yield of 21 kT of TNT [2]. This was the first underwater test of a nuclear device, and only the third recorded nuclear experiment to date. The target array shown in Figure 3 was set up to allow data collection for all types of available ships. Most of these ships were old, obsolete, and due to be decommissioned. The device was suspended beneath LSM-60 (Landing Ship Mechanized), which was destroyed in the initial shockwave travelling upward and the subsequent high-velocity water column. The nearest ship to LSM-60 was the USS Arkansas (BB-33). She was located 223 yds from the center of the burst, angled just over 10 degrees from the starboard beam or 107 degrees relative bearing. Figure 3 shows the relative position of the bow pointing generally east. The Arkansas was moored by both bow and stern mooring anchors to maintain her relative orientation to the blast, which is nearly starboard broadside to the zero point [1]. These mooring anchors provided significant resistance to lateral as well as vertical movement.

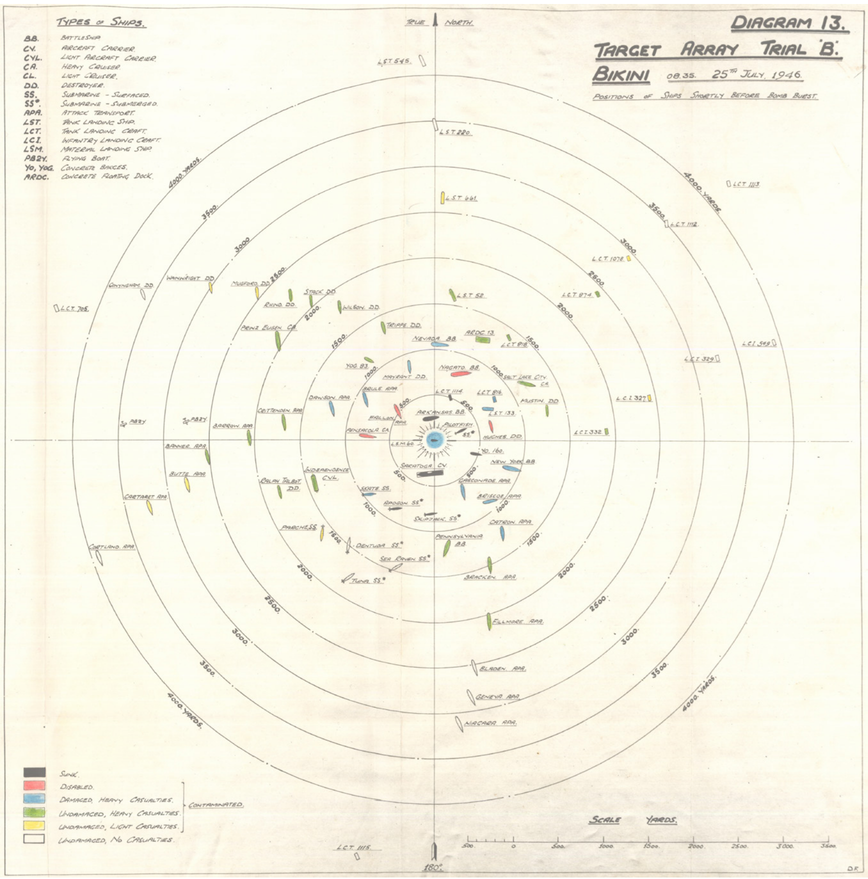

Figure 3., Crossroads Baker Ship Target Array (LANL Archives)

The USS Arkansas

The Battleship USS Arkansas BB-33, shown here underway in Figure 4, was a Wyoming class battleship commissioned in September 1912. She was 562 ft long, had a 106 ft beam and 30 ft draft [1,8]. Throughout her long career, she served in both the Atlantic and Pacific fleets. She spent most of World War I escorting ships across the Atlantic and training Naval Academy midshipmen in their summer cruises. During World War II the Arkansas participated in the invasion of Normandy in the Atlantic, as well as the battles at Iwo Jima and Okinawa in the Pacific. After the end of World War II, the Arkansas was designated obsolete and was set for decommissioning. As a final service to the nation, she was added to the target array for Operation Crossroads. She was sunk within seconds of the detonation of the Baker device due to severe hull buckling and collapse on the starboard side (nearest the blast); her port side was significantly less damaged. The Arkansas now lies at the bottom of the lagoon along with the 13 other ships sunk in the test series including the carrier USS Saratoga; three submarines: USS Pilotfish, USS Skipjack, and USS Apogon, and several other ships [8].

Figure 4. USS Arkansas BB-33: USS Arkansas Underway,
https://www.history.navy.mil/our-collections/photography/us-navy-ships/battleships/arkansas-bb-33/80-G-229753.html

Test Data from Baker

The overall purpose of Operation Crossroads was to obtain data on the effects of nuclear explosives on naval vessels above and below the water. During the Crossroads tests, there were many data collection efforts. One was to obtain pressure data in the water, and in the ships that were in the array. Some ships were more instrumented than others. Unfortunately, the pressure data from the Arkansas, like other ships closer to surface zero in the Baker test, was lost when the ship was sunk [5,6]. As an alternative to direct pressure gauge measurements, the pressure in the water around the blast was recorded, and is presented here as a reference for further calculations shown in Table 1.

Table 1: Values of peak pressure in the water halfway between surface and the bottom [5].

Distance from Zero Point (ft)	835	1084	2060	5000
Gauge Pressure (psi)	7000	4400	1400	330

The water velocity directly above bomb was recorded at around 11,000 ft/sec. The pressure gauges just below the surface of the water measured 4800 psi at 835 ft from zero point for <1 millisecond. [6]. These data points are important for the following basic physics calculation.
Physics Calculations

Here is the basic physics equation and relationship to determine approximate theoretical relationships and expected values. This is what is colloquially referred to as a “back of the envelope” calculation.

$$\text{Force} = \text{mass} * \text{acceleration} = \text{pressure} * \text{area}$$

The USS Arkansas displaced 26,000 tons = 23586803 kg (mass) and had a projected area of A= 29,916 ft^2 = 2779 m^2. This simple geometry uses flat plates to approximate the hull of the Arkansas in the water. 4800 psi = 3.309E7 Pa. Rearranging the terms above, we see that:

$$3.309E7 \text{ Pa} * 2779 \text{ m}^2 = 9.19805E10 \text{ Newtons (N)} = 23586803 \text{ kg} * \text{acceleration}$$

$$9.19805E10 \text{ N} / 23586803 \text{ kg} = 3900 \text{ m/s}^2 = 398 \text{ g}$$

This acceleration of ~400 g estimated here to have hit the Arkansas from the bottom lines up very well with the maximum recorded accelerations from other ships that were instrumented with indenter gauges, putty gauges, and reed-type acceleration gauges. The ships closest to the zero point of Baker that were not sunk were the USS Pensacola, USS New York, and USS Nevada [3].

Regardless of their distance from the zero point, the ~400 g shocks were not of sufficient duration—less than a millisecond—to cause substantial lift to any of the ships in target array [3,6]. This can be understood in the analogy of a punch vs a shove. The longer duration of the shove will cause substantial movement. To lift a warship like the Arkansas, the duration of the acceleration would have to be much longer than the millisecond that was recorded in this test.

As the Arkansas was anchored to the sea floor, both bow and stern, this provided substantial resistance to any lifting and tipping movements caused by the blast. The resistance from the mooring anchors possibly resulted in an increase in the damage experienced by the Arkansas from shot Baker. These facts, and the physics calculated above, make it clear that the Arkansas wasn't going anywhere but down. Due to the mass of water falling from the large water column, the Arkansas is assumed to have been swamped and pushed into the lagoon bottom with substantial force. She now rests inverted on the bottom of the lagoon showing the damage from the blast. The mooring anchors are still attached to the bow and stern, indicating further proof that she was not lifted vertically into the water column [8].

Hydrodynamic Physics Simulation

When looking into the fate of the USS Arkansas, the authors wanted to exercise the capability of Los Alamos High Performance Computing (HPC) using a validated and well-understood hydrodynamic multi-physics code. This simulation provides a good validation of the code, relative to the data collected as well as visible proof that the code can simulate a complex underwater burst. For this calculation, the authors used the Cassio code, a LANL designed hydrodynamic physics code, using the inputs constructed from available references as well as NV-209, the official unclassified test history [2]. Cassio is an Eulerian-mesh code with adaptive mesh refinement (AMR) constructed at each time-step to place maximal computational power where the physics is most dynamic. Due to the complications of simulating the geometry of a 3D ship on the water on a 2D axisymmetric computational grid, along with the mooring lines holding her down, the author's simulated the blast in the code without the USS Arkansas in the simulation.

Figure 5 shows a density color plot of the explosion at different time steps. The pressure plot and

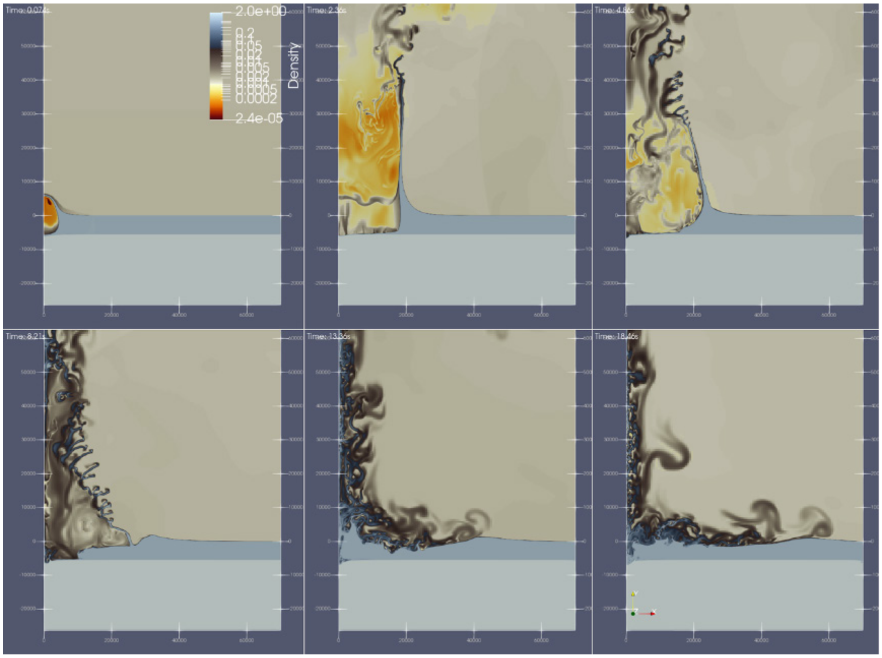

Figure 5: Cassio Simulation of Crossroads Baker in Density Color

corresponding data corresponds to the pressures recorded in the test (not shown here). This was done primarily to understand and have a 1st order validation of the code and how it is calculating the blast in the water. Having a way to visualize the test and understand the data was very valuable to have high confidence in the conclusions presented below. Although there is not a way to provide a direct comparison, the photographs in Figure 6 taken from the film "Bombs at Bikini" correlate visually to the simulation.

Figure 6: Time sequence photos of Crossroads Baker (from film Operation Crossroads (LANL Archives))

Conclusion

After review of the USS Arkansas, the two shots Able and Baker, and the shock data from both of those tests, we were able to understand the forces, shock duration, and acceleration that happened during the test. The large inertial mass of the battleship, her broadside orientation to the blast, the limited momentum transfer-short pulse duration of the water shock, and the fact that she was moored to the bottom of the lagoon by both bow and stern gives confidence to the conclusion that the USS Arkansas was not thrown substantially into the bulk of the water column.

The data from the hydrodynamic simulation lines up well with recorded data from test Baker. The basic physics calculation also validates the forces and accelerations likely experienced by the USS Arkansas. This provides a point of validation for the code as well as helping to definitively bust the myth of the dark patch in Figure 2 being the USS Arkansas on end.

What caused the dark patch in the photograph that has sparked the myth and the debate? The consensus among many experts here at LANL and those who study this is that the soot from the boilers on the Arkansas was shaken loose from the Crossroads Able test and was pushed out of the stacks as the pressure wave from the Baker test hit the bottom of the ship and travelled up through it, leaving the cloud of soot mixing with the water vapor just above the ship in the photograph.

Many thanks to historian Alan Carr, and retired scientist Tom Kunkle for their substantial contributions to this article.

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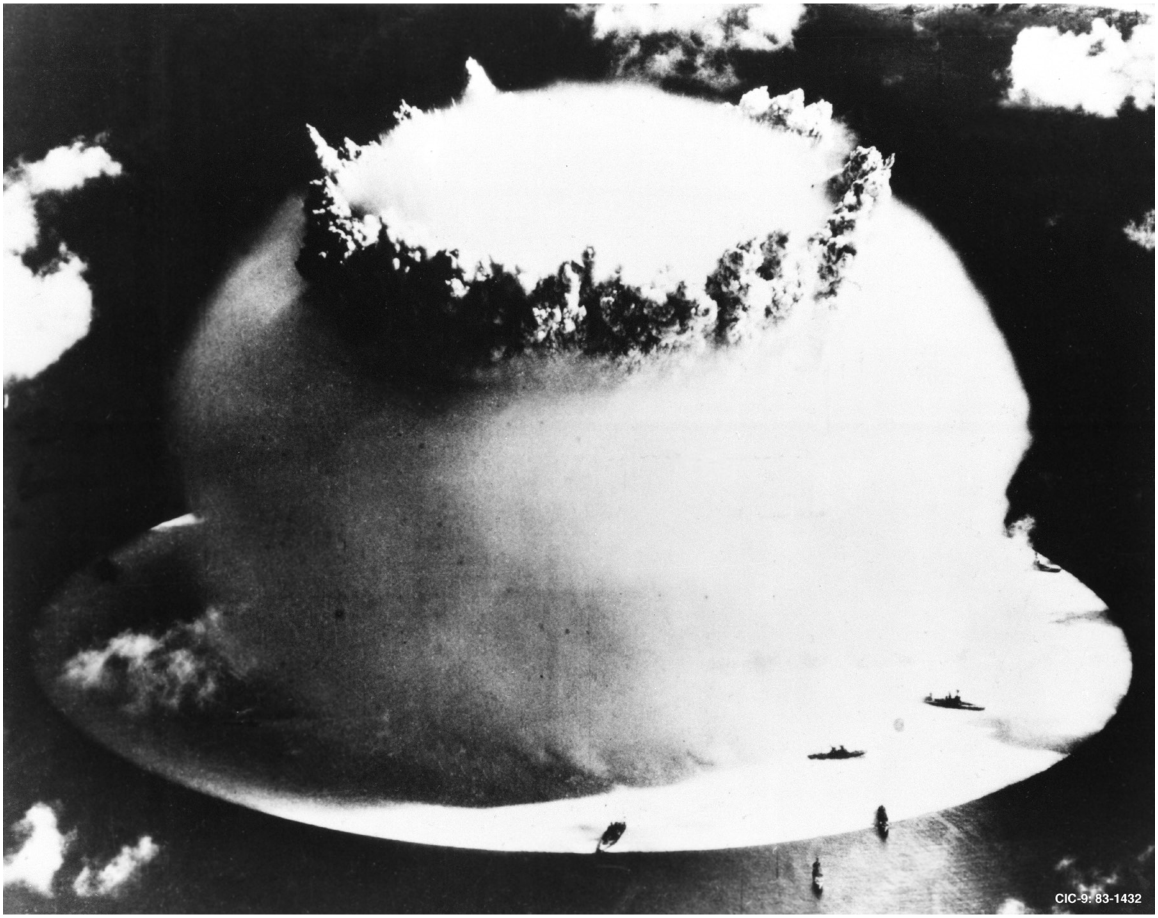

photo of Crossroads Baker test shot, 25 July 1946. (LANL Archives))

Non-Strategic Nuclear Weapons on the Future Battlefield

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Department of Energy, National Nuclear Security Administration (NNSA)

Introduction

United States policy and national security strategy recognize the existential threat of nuclear weapons and the tenuous peace they preserve: nuclear weapons are the most piowerful instruments of war and the ultimate strategic deterrent. While certain nuclear weapon types are indeed so powerful that the detonation of a single warhead may cause such horrific damage as to induce an adversary to stand down, other nuclear weapon types produce significantly more limited effects. While nuclear doctrine of the Cold War-era threat hinged on an exchange of nuclear super bombs between the Soviet Union and the United States, contemporary conflict and competition requires a more nuanced approach that flexes the range of the nuclear deterrent.

Current U.S. nuclear doctrine defined in the 2018 Nuclear Posture Review (NPR) references "modest supplements" to the United States' non-strategic nuclear weapons capability and terms for their use.[1] In 2021, Secretary of Defense Lloyd Austin introduced the concept of integrated deterrence, outlining the need for combined nuclear and non-nuclear capabilities for deterrence and conflict escalation, potentially including battlefield use of lower yield nuclear weapons.[2] The forthcoming Nuclear Posture Review (NPR) is likely to include references for nuclear weapons use in a theater context. As U.S. nuclear and deterrence doctrine evolve to address the challenges of the current era of strategic competition, U.S. military war planners must be prepared for the potential employment of U.S. non-strategic nuclear weapons and become experts in their ethical use. <u>The United States and its allies should consider a hybrid framework that draws on utilitarianism and just war theory to evaluate courses of military action that include the use of non-strategic nuclear weapons on the battlefield.</u>

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Non-Strategic Nuclear Weapons

There is no agreed upon definition for non-strategic nuclear weapons. Some distinguish strategic from non-strategic nuclear weapons based on strict interpretation of arms control policy: weapons not covered by the New START treaty are considered "non-strategic."[3] Others make the distinction based on delivery system and whether the weapon has intercontinental range.[4] A third definition reflects both the intended effect of the nuclear weapon and its technical specifications.[5] According to this definition, non-strategic nuclear weapons are typically low in yield and designed to produce limited destructive effects in order to achieve specific, tactical objectives on a battlefield.[7] The use of the term "non-strategic nuclear weapons" in this paper aligns most closely with this third definition. A strategic attack is "specifically selected to achieve national strategic objectives" and "seeks to weaken the adversary's ability or will to engage in conflict … without necessarily having to achieve operational objectives as a precondition." In contrast, tactical operations are limited in scope, directly support a commander's scheme of maneuver, and are limited to an area of military operations.[8]

In general, an explosion is the extremely rapid release of energy and vigorous expansion of high-temperature and high-pressure gasses caused by a reaction. Conventional explosions are created by a chemical reaction; nuclear explosions by nuclear fission and nuclear fusion reactions.[9] The energy released by a nuclear explosion produces four types of destructive effects: blast, thermal radiation, and initial and residual nuclear radiation. Electro-Magnetic Pulse (EMP) will not be addressed with regards to non-strategic nuclear weapons. The explosive blast itself is the primary destructive force in a nuclear detonation.[10] In this way, nuclear weapons are similar to conventional weapons. However, the blast produced by a nuclear explosion can be thousands (or millions) of times more powerful than a conventional explosion and requires significantly less explosive material.[11]

The nuclear weapon yield, or the amount of energy produced by the explosive blast, is measured by the kilotons of trinitrotoluene (TNT) required for a conventional explosion that releases the same amount of blast energy.[12] For example, a one kiloton nuclear weapon yields the same explosive power as 1,000 metric tons of TNT. A nuclear weapon is typically considered non-strategic at yields between 1 and 10 kilotons.[13] For comparison, the 2020 conventional explosion in Beirut produced a blast equivalent to about 300 tons of TNT; the 1921 explosion of a fertilizer plant in Oppau, Germany that killed 565 people was equivalent to a 1 kiloton blast; and the nuclear bombs dropped on Hiroshima, Japan in 1945 produced an estimated 15-kiloton blast.[14]

In addition to the blast, nuclear explosions emit thermal radiation: light and heat that can cause injury to the unshielded and spark fires. Additionally, a nuclear blast produces harmful initial and residual (fallout) nuclear radiation. Though the range of initial radiation can extend beyond the range of the blast, most within range of the initial nuclear radiation are likely to be destroyed by the blast itself. The explosion also disperses very small radioactive particulates over the local blast area. These particulates produce ionizing radiation at extremely high dose rates in the hours immediately following the blast, posing a significant health hazard to those exposed to the particulates. While it may take months or years for the radioactive material to completely decay away, the residual radiation decays to levels low enough to permit movement in and through the area within weeks, days, or even hours, depending on the yield of the nuclear weapon.[15] The extent of residual radiation can be mitigated in the way the weapon is employed.[16]

U.S. Nuclear Doctrine.

The foremost objective of U.S. nuclear policy and strategy is to deter aggression and preserve peace.[17] U.S. nuclear deterrence strategy has evolved since the development of nuclear weapons, characterized by two predominant approaches: the straightforward concept of symmetric deterrence that dominated Cold War nuclear strategy and tailored deterrence strategies, which were introduced during Kennedy administration and gained prominence with the collapse of the Soviet Union.[18] The development of second generation, thermonuclear bombs within five years of the Japan bombings introduced nuclear weapons with yields thousands of times more powerful than the original A-bomb.[19] Combined with long-range, accurate delivery platforms, these sophisticated nuclear weapons systems held cities and valuable targets an ocean away at constant risk of total annihilation.[20] Great powers pursued robust second-strike capabilities, capable of delivering a retaliatory strike at levels of unacceptable destruction, even following a debilitating nuclear attack.[21] The guarantee of massive nuclear reprisal set the doctrine of Cold War-era deterrence.

A more complex threat landscape emerged with the fall of the Iron Curtain, marked by the rise of regional nuclear powers, increasing sophistication of conventional weapons, and the proliferation of non-nuclear weapons of mass destruction.[22] To match these demands, the United States adopted a more nuanced approach that emphasizes the design of specific deterrence strategies tailored to each situation or threat and broadens deterrence to include non-nuclear capabilities.[23] The evolution of deterrence culminates in the emerging strategy of integrated deterrence, which seeks to seamlessly combine conventional and nuclear military capabilities with emerging technologies and across all domains of operation.[24, 25]

According to U.S. nuclear policy, tailored deterrence requires increased diversity in nuclear capabilities to expand flexibility and enable limited, graduated response.[26] Specifically, the 2018 Nuclear Posture Review (NPR) outlines the use of non-strategic nuclear weapons to fill any perceived gaps in U.S. deterrence capability and increase flexibility in deterring regional aggression.[27] Though the United States recognizes the complementary role of non-nuclear capabilities in deterrence, they "cannot replace U.S. nuclear forces for this purpose."[28] While the 2018 NPR does not enable "nuclear war-fighting," U.S. policy recognizes the use of nuclear weapons "should deterrence fail" and calls for the integration of nuclear and conventional forces to "respond with whatever force is necessary in a nuclear environment." According to theory, these capabilities, in turn, further increase deterrence.[29]

Russian Nuclear Doctrine

In many ways, U.S. interpretation of Russian nuclear and deterrence doctrine informs U.S. nuclear policy and strategy. For example, the 2018 NPR highlights elements of U.S. nuclear strategy developed in response to the purported Russian strategy of "escalate to de-escalate": coercing the end of a conventional conflict through the limited use of nuclear weapons.[30] However, Western scholars of nuclear deterrence and Russian strategy do not agree that "escalate to de-escalate" accurately describes Russian nuclear doctrine.[31]

In 2020, Russia released its Basic Principles of State Policy of the Russian Federation on Nuclear Deterrence, the first open publication on Russian nuclear doctrine and posture. Basic Principles describes the primary aim of Russia's nuclear forces as defensive by nature: to provide sufficient deterrence from nuclear or conventional war and guarantee protection and integrity of the state.[32] According to declared policy, the Russian Federation considers nuclear weapons "exclusively" as a means of deterrence.[33] However, Russia maintains the right to use nuclear weapons as "an extreme and compelled" measure in response to the use of nuclear weapons, other weapons of mass destruction, or the use of conventional weapons when the "very existence of the state is in jeopardy".[34]

While this transparent description of Russian strategy does not completely repudiate the concept of "escalate to de-escalate," they present a more complete description of the goals of Russian nuclear doctrine: to control escalation and end conflict – whether nuclear or conventional – on terms favorable to Russia, particularly in a regional conflict and to ensure the integrity of the Russian territory. U.S. Air Force General John E. Hyten, when serving as the Commander of U.S. Strategic Command, explained that Russian doctrine is not "escalate to de-escalate, it's escalate to win."[35] While Russian president Vladimir Putin assures that Russian nuclear use policy is "all very clear and specific"[36], comments by Russian officials sometimes present options for nuclear use beyond this doctrine. In reality, Russian nuclear doctrine serves as guidance for policy and organization of the Russian defense departments, not a manual for how to wage war.[37]

Whatever the true nature of Russia's nuclear strategy may be, there is an emphasis on

Figure 1, Russian troops load a missile onto an Iskander-M launcher during a 2016 exercise.[38]

nuclear weapons in Russian military doctrine and modernization.[39] Russia maintains a diverse and modernized arsenal of strategic and non-strategic nuclear weapons and is currently in the middle of a decades-long program to further modernize its nuclear forces.[40] The range of capabilities afforded by this modern nuclear force would enable the flexibility required to implement a deterrence doctrine that extends beyond simple deterrence and toward ensuring success in a regional warfighting.[41] These principles were demonstrated in the Grom 2019 strategic command staff exercise, which tested Russia's defensive reaction to conflict escalation[42] with integrated strategic and non-strategic capabilities.[43]

Framing the Ethics of Non-Strategic Nuclear Weapon Use

Academics, decisionmakers, and historians have engaged in debate on the ethics of nuclear weapons since their only operational use by the United States against the Japanese cities of Hiroshima and Nagasaki. Indelibly influenced by this history, nuclear ethics typically centers on the effects of use of nuclear weapons against a civilian populace, the perceived indiscriminate nature of nuclear weapon effects, and an assumption that a nuclear explosion will cause mass human destruction and environmental damage.[44] While decisionmakers must contemplate these very real consequences when considering the use of strategic nuclear weapons, they do not apply to the same degree when framing the ethics of non-strategic nuclear weapons on the battlefield.

Utilitarianism frames challenges and choices by their outcomes, seeking the greatest good and the least harm to the largest number of people.[45] Decisionmakers applying a utilitarian framework enumerate and quantify the costs and benefits of each course of action and choose the alternative that maximizes the ratio of good to bad.[46] Utilitarianism is widely used to address strategic challenges facing government decisionmakers including policy decisions, judicial choices, and crisis management such as disaster response.[47] However, decision makers applying utilitarianism must beware of its shortcomings in practice: undervaluing long-term and indirect effects and the inclination to determine, ultimately, that ends justify whatever means.[48]

Decisionmakers can leverage utilitarianism to evaluate the use of non-strategic nuclear weapons on the battlefield because the most significant effects – the destructive and harmful effects produced by the explosion itself – are predictable and quantifiable. Furthermore, decisionmakers can pragmatically compare the use of non-strategic nuclear weapons against alternative courses of action, such as the use of conventional weapons. However, utilitarianism alone is an insufficient tool in framing the use of non-strategic nuclear weapons as it may fail to adequately capture indirect externalities and long-term effects of a nuclear explosion of any size. More importantly, utilitarianism alone is incompatible with just war tradition and laws of conflict, which prescribe foundational ethical and legal principles that guide the United States in warfare.

Putting Theory to Practice

Just war tradition defines a set of rules shared between people at war.[49] These rules have evolved into the treaty and international laws governing armed conflict.[50] To frame the challenge of non-strategic nuclear weapons and evaluate the ethics of their use on the battlefield, decisionmakers begin with just war tradition and the law of armed conflict, then leverage utilitarianism to assess potential courses of action against the criteria established in these conventions. The first condition of just war, jus ad bellum, defines rules that justify going to war.[51] Decisionmakers should use the remaining criteria of jus in bellum, just conduct in war, and jus post bellum, just conduct during post-war reconstruction, as guidance to sufficiently enumerate short and long-term consequences of a tactical nuclear strike.

Within the criteria that define jus in bellum decisionmakers should consider the benefits of the use of non-strategic nuclear weapons – the likelihood of achieving the tactical military outcome – against its negative effects. Though it is hard to imagine, the preponderance of direct effects produced by a non-strategic nuclear weapon would be confined to the battlefield. Nonetheless, incidental harm to civilians is inevitable. Decisionmakers should weigh the use of non-strategic nuclear weapons against criteria delineated in legal codes mandating distinction between civilian and military targets, restraining disproportionate incidental harm to civilian life or objects, and prohibiting the use of weapons that cause unnecessary suffering.[52] Jus post bellum offers a useful prompt to consider the long-term effects of nuclear battle, such as denied access to land and long-term environmental effects of radiation to water and soil.[53] In accordance with utilitarian philosophy, decisionmakers should select options that achieve military objectives with the least harm rather than options that bring more decisive military victory.[54]

Realistically, the use of a non-strategic nuclear weapon during conflict will also produce indirect effects beyond the kinetic effects of the weapon. These indirect effects are likely to be greater in scale than the tactical aims for which the weapon was intended. This concept of disproportionate effects underpins nuclear deterrence theory. For example, the U.S. Joint Publication on Nuclear Doctrine explains that the "employment of nuclear weapons can radically alter or accelerate the course of a campaign. A nuclear weapon could be brought into the campaign […] to escalate the conflict to sue for peace on more favorable terms.[55]" Decisionmakers should consider that the use of a non-strategic nuclear weapon in conflict may preclude further harm resulting from continuing warfare; official adoption of this strategy may deter future conflict. However, the introduction of a nuclear weapon would fundamentally and unpredictably alter a conflict, a consideration reflected in statements by U.S. and Russian policymakers that a nuclear war cannot be won and should never be fought.[56] As is often the case with complex problems, analyzing these effects requires theoretical, probabilistic projection and is extremely difficult to validate.

Planning Now for the War of the Future

The complex issue of non-strategic nuclear weapons demands analysis using more than one ethical lens. National security policymakers and planners should leverage an approach that draws on numerous frameworks, such as utilitarianism and just war theory, to thoroughly and effectively evaluate military actions that employ non-strategic nuclear weapons. Operational planners should apply this framework iteratively to evaluate specific courses of action, using the results to tailor new alternatives. Decisionmakers, policymakers, and operational planners should practice this assessment now to build capacity and muscle memory in the ethical use of these instruments of war.

The era of Great Power Competition demands integrated and highly calibrated implementation of U.S. military capabilities to meet national security challenges across competition, change, conflict, and crisis.[57] This will require a sophisticated and practiced understanding of the role of non-strategic nuclear weapons in deterring nuclear and conventional conflict and, should deterrence fail, achieving U.S. national objectives at the lowest level of damage possible. U.S. decisionmakers and operational planners must become experts in all manners of potential warfare with great power competitors to ensure the comprehensive effectiveness of the United States' nuclear deterrent should it face non-strategic nuclear weapons in conflict.

Figure 2,Unarmed Minuteman III intercontinental ballistic missile launches during an operational test.[58]

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    The U.S. Department of Homeland Security (DHS) considers dose rates above 10 rad/hour to be dangerous and limits emergency response activities to time-sensitive, mission-critical operations such as rescuing identified injured survivors. DHS considers dose rates of 0.01 rad/hour to 10 rad/hour to be potentially hazardous for emergency responders and cautions that cumulative radiation exposure at this level should be monitored. (“Quick Reference Guide: Radiation Risk Information for First Responders Following a Nuclear Detonation,” December 2016, https://www.dhs.gov/sites/default/files/publications/Quick%20Reference%20Guide%20Final.pdf)

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Innovative Analytic Strategies to Address Challenging Counter-WMD Problems

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Defense Threat Reduction Agency RDCXA / RDCXS

Introduction

The Defense Threat Reduction Agency Counter WMD Technologies Department (DTRA-RD/CX) within the Research & Development Directorate is focused on providing the National Security Enterprise with improved tools and methods supporting critical functions across the kill chain in order to hold adversary WMD weapons, facilities, systems, infrastructure, and networks at risk. This mission focus includes the full gamut of WMD and enabling technologies, addressing Chemical, Biological, Radiological, Nuclear, and Explosives weapons, as well as delivery systems (e.g., missiles) and protective systems (e.g., underground facilities). These research and development activities are aligned with doctrine set forth in Joint Publication 3-40, "Joint Countering Weapons of Mass Destruction," 27 November 2019. As these new tools and methods are transitioned to partners, one precept remains inviolable: a trained specialist is always in the loop, whether for target characterization, weaponeering[1] solution development, or attack planning to meet Commander's intent.

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The critical kill chain functions remain much as they have been since World War II: identify the target, characterize the target and its vulnerabilities, evaluate weapons performance against the target to achieve the desired outcome, plan and execute an attack, and assess results. Driving R&D for new tools and methods supporting these functions is the sheer number of targets, the increasing sophistication of our potential adversaries, emerging technologies enabling new threat modalities, and the growing awareness among adversaries of US capabilities, tactics, and weapons systems performance.

The Combatant Commands and the National-level Agencies have increased the tempo of surveillance and collection activities in response to the increase in number of targets. In turn, this has resulted in expanding data repositories, but the analytic processes to convert data in these repositories into useful information has struggled to keep up. The problem is exacerbated, especially as the data repositories migrate to the cloud, through lack of common standards for data structures, query syntax, and expressions of uncertainty, adding additional complexity to the analysis workflows.

Emerging technologies – whether for improvised explosive devices, novel chemical or biological warfare agent production, or other WMD – require developing in-depth understanding of acquisition pathways, and both stochastic and deterministic science-based modeling tools for weapons effects analysis, collateral damage predictions, and sensitivity studies. Analyzing emerging acquisition pathways is important for identifying critical node vulnerabilities to disrupt an adversary's capabilities short of full-scale conflict. As stated in JP 3-40, "WMD defeat involves the Joint Force Commander employing tailored capabilities to neutralize or destroy weapons and agents; delivery systems, and materials, facilities, and processes, including the functional or structural defeat of hardened targets.[#2] The programs discussed below directly address these requirements.

Where a number of targets can logically be grouped into populations of similar entities, the time-tested approach of developing templates can yield useful preliminary analysis results in support of these mission objectives. Historically, applying templates has been used to address problems consisting of a hand full of entities, not thousands, as is the case, with underground facilities today. Grouping across such a large population also relies strongly on the metadata associated with the individual targets, not just the parameters input into weapons effects models. This metadata may be resident in separate data repositories, further complicating the analyst's job.

Three current programs under the Counter WMD Technologies Department illustrate how DTRA-RD/CX is tackling these challenging problems through application of advanced technologies such as High-Performance Computing-enabled modeling, Machine Learning for information extraction, and optimization strategies for evaluating courses of action.

Hard Target Characterization

An advanced technology enhancement to the Underground Target Analysis System (UTAS) is under development by the Target Assessment Technologies Division (CXA) within CX. DTRA is a founding partner addressing the global proliferation of underground facilities (UGF). CXA contributes engineering-domain expertise to develop characterizations of adversary UGFs, and research and development efforts to realize improvements in fidelity and confidence in the characterizations, as well as process improvements to increase analytic throughput in a resource-constrained environment. Under current workflows, characterizations are labor-intensive with focus placed on addressing priority target requirements. Typically, these priority requirements address some of the most complex and unique adversary UGFs. This impacts scheduling and executing the characterizations and requires analytic insights gained through years of experience. As a corollary, the lower-priority targets tend to be less complex and more broadly similar where automated tools can more effectively be applied.

The starting point for any characterization, automated or not, is to query databases across the Federated intelligence and warfighter communities. Many of these databases are migrating to the cloud, where software agents can readily perform the ingest and filtering functions. Data includes terrain, imagery, geology, and all-source intelligence. Functional flows supporting DTRA's automated Hard Target characterizations are shown in Figure 1. Software agents are being coded in modern software development frameworks and applied in the classified version of Amazon Web Services, C2S.

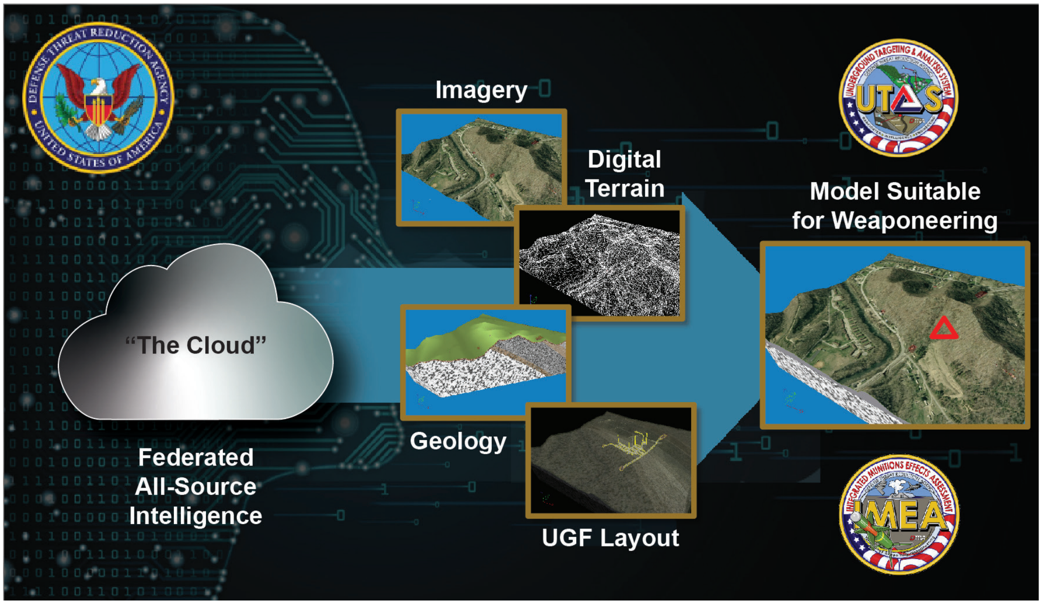

Figure 1. Intelligence information and technical data flow from "the Cloud" to support DTRA's automated target characterization process, yielding a three dimensional model suitable for use with existing weaponeering tools. <Author created>

Central to machine-aided target characterization is the development of automated feature extraction from the data collated by the agents, such as dimensional information, orientation, and placement of externally-observable features into the terrain. The approach followed incorporates the development and training of four different, independent Machine Learning (ML) algorithms, integrated into an ensemble to yield increased confidence in the results and guard against hidden flaws in any one particular ML routine. Training and validation data sets for the ML routines are carefully curated from relevant historical characterizations, as well as high-fidelity domestic ground-based geospatial data collected at surrogate accessible UGFs. Data sets are further partitioned to account for possible biases associated with regional variations in construction practices. Algorithms for the ML routines and management of information records are implemented in Python, C++, and Java.

Following the extraction of relevant features, information is conveyed to an expert system, Automated Reasoner, to create visualizations of the UGF based on the observable features using a ruleset developed through extensive analysis of historical characterizations and interviews with domain experts. Visualizations, after review by an experienced analyst, serve as the basis for generating a three-dimensional UTAS-compatible model of the UGF. Validated UTAS models are approved for use in evaluating weapons effects against the target. Automated characterization tool development is also closely coordinated with the efforts to automate weapon-target interaction calculations, discussed below, to ensure compatibility in data structures, definitions, and assumptions.

The objective architecture for automated characterization includes a user interface Workbench, process auditing, and mandatory manual review gates. The current development schedule is focused on transitioning the Version 1.0 tool, addressing a high-priority target class, to partners for acceptance and integration into approved workflows in FY22. Spiral development will continue to add additional target classes to the automated tool set capability.

Automated Target-Weapon Interaction Calculations

Another program under CX is applying advanced technologies to yield process improvements for evaluation of weapons effects applied against targets. The genesis of this project parallels the rationale underlying automated target characterizations, that of addressing ever-growing backlogs of target planning requirements. The weapons effects calculation tool development program builds upon the foundation of DTRA's combat-proven Integrated Munitions Effects Assessment (IMEA) weaponeering tool for hard and/or CWMD targets.

IMEA is a suite of moderate-fidelity physics-based codes accessible through a shared user interface. The codes run on high-end desktop PCs and are supported by a server-based calculation engine for intensive operations such as Monte Carlo simulations. Candidate weaponeering solutions are assessed using a stochastic approach to account for uncertainties in the input data (e.g., the target characterization generated using traditional methods or the machine-aided characterization tool) and decision theory optimization to address missing information required for rigorous evaluation of courses of action. User selections in the analysis are weapon type, fuzing, aimpoint, and delivery geometry. The large number of candidate attack solutions results in long execution times, problematic when the weaponeering process is constrained by the timelines required by active combat operations. Inevitably, the experienced analyst has to make judgement-driven decisions to down-select attack options prior to actual evaluation in IMEA. "Proper weaponeering and hazard modeling help the Joint Force Commander employ the proper resources, understand the potential consequences of execution, and minimize collateral damage." Targeteers and battle staff already address these needs: the automated tools under development by DTRA are intended as a force multiplier. Weaponeering by analysts with limited experience, unable to make these expert decisions, can become either an unacceptable commitment of resources per individual target, or generates solutions of uncertain utility.

With the dual objectives of achieving greater weaponeering throughput, and of enabling beginning analysts to become more productive quickly, the machine-aided target-weapon interaction calculation engine effort is implementing extensions operating on top of the baseline IMEA environment. The first iteration of this was the development of a "Warfighter Wizard" that applies optimization techniques to the choice of fuzing and aimpoint selection. The Wizard also allows a timely evaluation of a larger solution space than is practical following historical analyst-intensive procedures. This Wizard has proven an effective enabler for beginning weaponeers to better shoulder some of the workload in CCMD targeting cells. Current development has shifted to incorporate more modern technical approaches to realize speed and scope improvements for all users, not just the beginners.

This effort has now implemented technology to quickly estimate the outcomes generated from the penetration and cratering codes in IMEA. The models in IMEA are of course traceable to first-principles and incorporate extensive testing data. This approach has resulted in up to five orders of magnitude decrease in the execution time for conducting a weapons effects assessment.

It is also important from an ethical perspective to recognize these tools are not a targeting or engagement system but rather an automated planning and decision-support system. A human is always in the loop to formulate the courses of action to hold the target at risk and address Commander's intent.

Further development in this area is planned to expand the scope of target-weapon interactions addressed by the modules to include air blast, fragmentation, and equipment damage scenarios. Interface modifications are planned incorporating Natural Language Processing, virtual reality, and visualization aids to increase efficiency in the decision-making process. The techniques proven in this effort are also extensible to other difficult problems such as non-kinetic defeat methods.

Functional Defeat

Functional defeat planning under CXA is a portfolio of modeling, testing, and solution development efforts collectively focused on WMD targets to expand options to meet Commander's intent beyond air-delivered kinetic attacks. These efforts were initiated in response to specific high priority mission requirements; on-going development is expanding scope of targets (pathways), range of possible actions (innovative non-kinetic mechanisms), and fidelity of vulnerability models in response to additional rapidly-emerging CCMD requirements.

The US national counter-WMD strategy defines pathway defeat as "comprising operations and activities to delay, disrupt, destroy, or otherwise complicate networks, links, and nodes that support the conceptualization, development, production, and proliferation of WMD."[3] These operations and activities can be applied across the full range of the conflict continuum, from clandestine operations through engagement with near-peer armed forces. Developing courses of action (COA) within this conflict space requires a high-fidelity understanding of process, material, and equipment vulnerabilities, not just structural vulnerabilities of the facility housing the WMD process of interest. Furthermore, the entire WMD acquisition pathway must be evaluated to uncover any nodes that present favorable trade-offs in mission risk/mission success to achieve Commander's intent. Minimizing collateral effects and consequences of action are other key considerations in the evaluation of multiple COAs for complex, difficult WMD targets.

Expanding options to deny, delay, or defeat adversaries' WMD programs by exploiting potential pathway vulnerabilities requires the development of a modeling, testing, and analysis approach that parallels the historical developments underlying our current capability to assess kinetic attacks. High-fidelity models, expensive both in time and resources, are developed and run for select high-value pathway nodes (which can include equipment or materials). The DTRA R&D efforts have developed finite-element models, discrete simulations, and other tools, and utilized custom code and commercial software such as MATLAB® and ANSYS®, to address problems across domains spanning virtually every engineering and scientific discipline. These models and simulations use a variety of computational resources, up to and including a High-Performance Computing (HPC) cluster to predict responses from a variety of attack vectors. CXA partners with other DTRA Departments as well as external organizations across the Federal Government to design and conduct tests to validate model outputs. Where CCMD needs require and time permits, validated high-fidelity models are used to evaluate specific solutions. The models are also used to enable a suite of decision support tools to address the broader problem set in counter-WMD missions.

A key axiom of the functional defeat program is the focus on defeating a capability, not simply a singular target entity. Expressed differently, the WMD pathway associated with a capability is an abstraction, but each instantiation of that pathway is composed of entities that function as a System of Systems (SoS). Developing a course of action against a capability examines the ensemble of vulnerabilities within this SoS which may consist of nodes of a process (e.g., manufacturing) located in a single facility or of nodes distributed across multiple locations. Current functional defeat analysis capabilities are limited to addressing at most a few nodes and/or locations, based on the maturity of the tools and methods. Solution sets also evaluate reconstitution times, as defeat modalities against many WMD targets do not necessarily seek comprehensive structural defeat – Commander's intent may be to functionally defeat a capability for some duration while other objectives in the OPLAN are addressed. CXA research has developed a Dynamic Failure Analysis Logic Tree allowing for evaluation not only of singular vulnerabilities but of cumulative and combined multi-node actions. Optimization methods for courses of action to counter these adversary SoS capabilities must take into account additional degrees of freedom within the parameter space to achieve convergence to a solution, or small family of solutions, that minimizes mission risk and maximizes mission success.

Future Complex Threat Network Defeat Research and Development

There are clear opportunities for each of the three research domains discussed above to leverage development tools, Machine Learning and Artificial Intelligence concepts, and optimization methods to address the broader scope of Complex Threat Networks (CTN). Analyzing Threat Networks for vulnerabilities and defeat strategies is an integral component of the Joint Intelligence Preparation of the Operating Environment (JIPOE) in support of the Joint Force Commander. Many threat networks can coexist, interact, and provide cross support within the Operating Environment. Analysis of many of these networks can be accomplished using graph-based numerical assessment tools such as CARVER.[4] Complex threat networks can require more sophisticated methods, such as the counter-WMD problem sets discussed above. A threat network can exhibit complexity from an analytic perspective for several reasons: transnational presence; close association with other networks, increasing the challenge to correctly associate nodes and links; and the need to apply physics-based modeling tools for nodal analysis. Joint Publication 3-25, "Countering Threat Networks," 21 December 2016, provides Doctrinal guidance for addressing these challenging problems. In particular when analyzing complex threat networks, it "must be noted…that conventional targeting is usually done during military operations/conflict, whereas much of the threat network targeting [analysis] is done by [United States Government] departments and agencies."[5] As a Combat Support Agency, DTRA's Research and Development programs continue to contribute to this mission.

Figure 2 illustrates numerous analytic disciplines that are being applied to the analysis of complex threat networks. The specific techniques current CX R&D programs have used are highlighted in each of the seven disciplines. There are rich opportunities to expand upon current work to further advance analytic capabilities in support of the JIPOE process. Future CX R&D activities include, for example, drawing from the work in target characterizations to develop an ensemble of ML algorithms trained on the outputs of the functional defeat HPC finite element models to significantly improve the speed at which vulnerability assessments are generated in support of COA optimization. Similarly, the equipment vulnerability models developed and validated as part of the functional defeat work could be incorporated into the automated target-weapon interaction tools for kinetic attacks. Each of the programs are working to increase the complexity of the problems they can

Figure 2. DTRA applies a rich portfolio of tools and methods to the problem of analyzing Complex Threat Networks, generating inputs for the Joint Intelligence Preparation of the Operating Environment (JIPOE) process in support of Joint Force Commanders. The methods and tools used or in development are highlighted above in each of the seven analytic domains. <Author created>

handle and to broaden their scope to include additional target classes or larger SoS.

Integrating these singular capabilities into a rich Threat Networks assessment capability will enable analysis of vulnerabilities in the influence and support infrastructures enabling adversary capabilities across the counter-WMD problem space. "Deterring threat networks is a complex and difficult challenge that is significantly different form classical notions of deterrence. Threat networks use asymmetric methods and weapons. They transcend operational areas, areas of influence, areas of interest, and the information environment."[6] Doctrine recognizes these unique challenges, whereby "complex threat network planning and operations require extensive coordination as well as innovative, cross-cutting approaches that utilize all instruments of national power."[7] DTRA-RD/CX has demonstrated significant progress in improving analytic tools supporting JIPOE for CTN, and continues to innovate in this problem space. Nevertheless, these advances remain tools to improve the person-in-the-loop analyst capabilities, whether responding to deliberate planning requirements or time sensitive targeting, rather than a step toward "SkyNet".

Notes

1. Weaponeering is the term used to describe the process of developing physics-based responses to application of weapons against aimpoints for a target. Attack planning, or targeting, takes the results from these various calculations for weapons effects and integrates them along with Commander's intent to create courses of action, probability calculations for achieving the desired outcome, and identifies execution parameters. CXA/CXS-developed tools directly support weaponeering and indirectly support attack planning.
2. JP 3-40, "Joint Countering Weapons of Mass Destruction," Chairman, Joint Chiefs of Staff, 27 November 2019, page IV-8.
3. Ibid, page II-9.
4. The CARVER method assigns weights to a threat in the categories of Criticality, Accessibility, Recuperability, Vulnerability, Effect, and Recognizability. These weights are then used in the JIPOE process to evaluate Course of Action.
5. JP 3-25, "Countering Threat Networks," 21 December 2016, page V-2.
6. Ibid, page I-4.
7. Ibid, page I-3.

References

JP 3-25, "Countering Threat Networks," 21 December 2016.

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Bush Wars: Chemical and Biological Warfare in Southern Africa during the Cold War

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This article is dedicated to the memory of Hermanus Stephanus de Manielle and Albert Max Bluhm

Introduction

"Now it is up to you, sir, to teach the wisdom"
– Former Selous Scout Timothy Bax, in a note to the author[1]

Though the Geneva Protocol prohibited the use of chemical and biological weapons in warfare as early as 1925, enforcement and international reaction when these attacks occur have varied. Chemical weapons had previously been used in Africa in the Spanish Rif War of 1921-1927 and the Italian invasion of Ethiopia in 1935-1936 with hardly a murmur in the international community, setting precedent that not all chemical weapon use was truly egregious.[2] This has persisted in the modern age, with significant discrepancies in the almost total lack of international reaction to approximately 30 alleged chemical weapon attacks in Sudan in 2016 contrasted with the immediate condemnation of the attempted Russian poisoning of Sergei Skirpal in the United Kingdom. This has led scholars to define a "hierarchy of victims" when it comes to chemical warfare, with white Western citizens being at the top and others, most especially black Africans, as being almost beneath notice.[3] Furthermore, chemical weapons programs, due to their generally localized effects, historically did not have the international condemnation biological or nuclear weapons programs did.[4] The use of chemical and biological weapons (CBW) against poor nations or indigenous insurgent groups in particular may be effective, as these targeted groups typically do not have the means by which to identify the agents used or differentiate them from naturally-occurring phenomenon. This fact has plagued Zimbabwe, for instance, in proving whether cholera and anthrax outbreaks were deliberately caused by Rhodesian security forces or occurred naturally.[5]

As southern Africa decolonized and transitioned to majority rule, the minority governments of Portugal, Rhodesia, and the Republic of South Africa (RSA) all used CBW to maintain control over their populations. The RSA, in its conflicts in Angola, would also allege that the Soviet Union and Cuban forces augmenting the Angolans used CBW to counter the tactical superiority of the RSA. Rhodesia and the RSA would extensively use CBW unconventionally to counter liberation movements within their borders. The continued ambiguity as to the use of CBW on the battlefield persists and may never be conclusively proven. These case studies demonstrate the difficulty of controlling CBW for the international community and are evidence that governments that are faced with their very survival will use any means at their disposal, regardless of international opinion.

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Background

> *"It is impossible to over-emphasise the malign effect that the Cold War had on Southern African affairs."*
> *Willem Steenkamp*[6]

Southern Africa was a hotbed of revolutionary movements during the Cold War. While some states – Zambia, Swaziland (now known as Eswatini), Botswana and Lesotho – all attained independence relatively peacefully from the United Kingdom, other states had much more violent independence struggles. Portugal's government would fight a series of bloody wars to retain its empire until the Carnation Revolution of 1975 formally ended the Portuguese Empire and granted those states – Angola, Mozambique and Guinea-Bissau – their independence.[7] Rhodesia would unilaterally break away from the United Kingdom and fight its own war against its black revolutionary movements, the Zimbabwe African National Union (ZANU) and Zimbabwe African People's Union (ZAPU), as well as battling Mozambique's Frente de Libertação de Moçambique (FRELIMO, who would rule the country following the Portuguese withdrawal). Rhodesia's war concluded in 1979 with the fall of the white minority government and rebranding of Rhodesia as Zimbabwe under Robert Mugabe's ZANU. Finally, the Republic of South Africa's (RSA) illegal occupation of South-West Africa (now Namibia) was contested by the South-West African People's Organization (SWAPO), and the RSA itself was faced with a series of guerilla movements aimed at ending apartheid, a system by which South Africa was entirely dominated politically and socially by its white minority.

South Africa would also invade Angola, support counter-revolutionary movements in Mozambique, and covertly destabilized Botswana, Lesotho, Malawi, Swaziland, Zambia and Zimbabwe.[8] The most prominent South African resistance movement was the African National Congress (ANC), who would take power in the first fully open election in South Africa in 1994, though not after a bloody near-civil war with a rival black liberation movement, the Inkatha Freedom Party. All the myriad interconnected communist revolutionary movements in Africa provided support and sanctuary to one another, with the Soviet Union and Cuba backing all of them. See Figure 1 for a map of southern Africa and the various blocs vying for power.

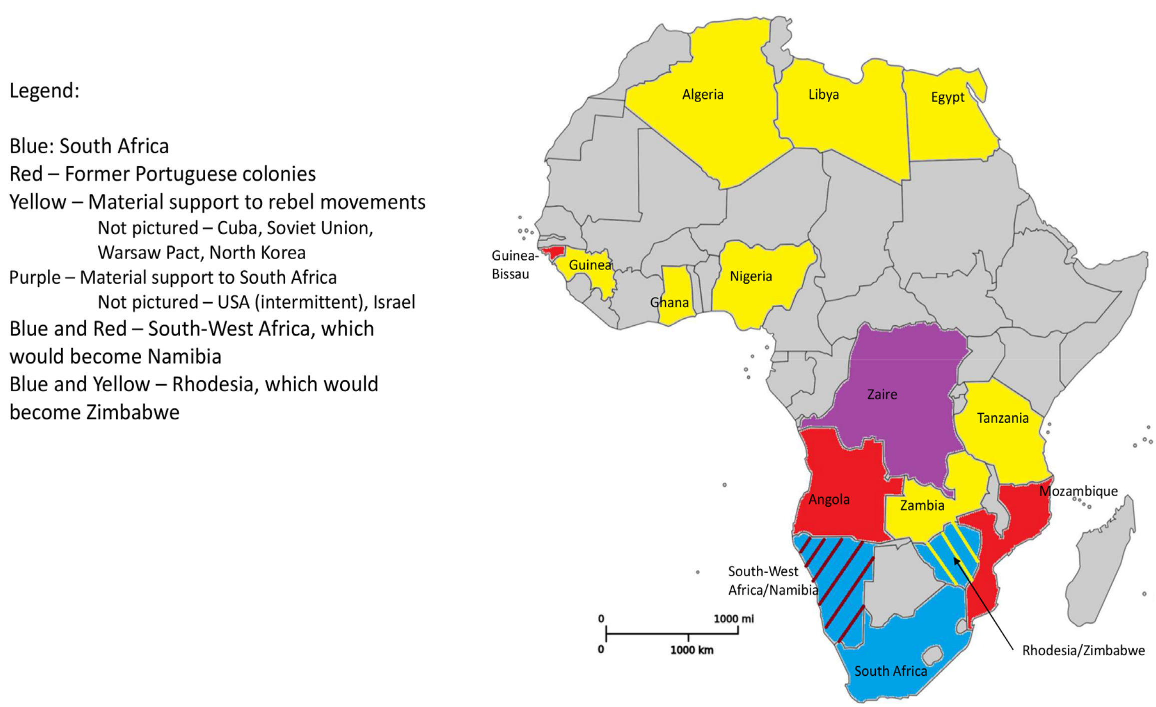

Figure 1: Map of Belligerents and Supporters in Africa during the Cold War (source: created by author)

The insurgent movements in Angola, Rhodesia, Guinea-Bissau, South-West Africa and the RSA issued a joint statement in 1968 at the Organization of African Unity (OAU) Algiers Assembly to condemn Rhodesia that announced an alliance of rebel groups.[9] In Angola the three revolutionary movements that resisted Portuguese occupation – the Movimento Popular de Libertação de Angola (MPLA), União Nacional para a Independência Total de Angola (UNITA) and the Frente Nacional de Libertação de Angola (FNLA) - immediately began fighting amongst themselves following independence in 1975. The FNLA rapidly collapsed, its remnants merging with the South African Defence Force (SADF) to form the core of the infamous 32 Battalion (Os Terriveis – The Terrible Ones).[10] Meanwhile RSA and Cuban intervention on the sides of UNITA and the MPLA prolonged the Angolan civil war, which continued until 2002 with the death of Jonas Savimbi, leader of UNITA.

The Portuguese struggle against its revolutionary movements began in 1961, the same year the ANC began its armed struggle against the RSA, and the Rhodesian Bush War began in 1964. South-West Africa's revolt began in 1966. Finally, in 1970, the RSA, Portugal and Rhodesia would sign a secret alliance, known as Alcora,[11] which may have been an acronym for "Aliança Contra as Rebeliões em Africa [Alliance Against the Rebellions in Africa]."[12] As the independence wars drug on, the RSA continued to see its allies – Portugal and Rhodesia – suffer defeat at the hands of revolutionary movements backed by the Soviet Union, with Portugal withdrawing from Africa in 1975 and Rhodesia collapsing in 1979. Under international isolation, the RSA came to see itself as both abandoned by its Western allies[13] and thus as the last bastion against a black communist takeover of Africa, which led it to develop nuclear, chemical and biological weapons in a desperate attempt to stave off defeat.[14] Nevertheless, South Africa's struggles would end with its withdrawal from Angola in 1989/1990, granting of independence to Namibia in 1990, and finally having free and open elections in 1994. This ended apartheid and, except for the Angolan civil war which would drag on for almost another decade, the major wars of Southern Africa.

Chemical and Biological Warfare in Southern Africa Overview

"One of the most serious errors, if not the most serious error, committed by colonial powers in Africa, may have been to ignore or under-estimate the cultural strength of African peoples." Amilcar Cabral, leader of Guinea-Bissau's Partido Africano para a Independência da Guiné e Cabo Verde (PAIGC), in a speech honoring the recently assassinated leader of FRELIMO, Dr. Eduardo Mondlane[15]

Portugal, Rhodesia, and the RSA all used CBW against the insurgent movements that they were fighting, with Portugal being the first country to use CBW against insurgents.[16] Portugal poisoned water supplies, drugged prisoners who were then thrown out of aircraft and executed[17], and extensively used defoliants to destroy crops.[18] Rhodesia in particular learned from these examples, with Rhodesian special forces unit the Selous Scouts repeatedly poisoning insurgent water supplies and providing insurgents with poisoned clothing and food clandestinely.[19] In several months of the Rhodesian war, more insurgents died due to CBW than from conventional operations by Rhodesian military units.[20] The RSA developed a nuclear program which successfully produced six gun-type weapons before being dismantled,[21] as well as an extensive CBW program code-named Project Coast under the direction of Dr. Wouter Basson.[22] The RSA's biological weapons program became the "second most sophisticated program"[23] in the world after the Soviet Union's, though much of South African CBW usage was in the form of poisonings, executions of prisoners of war, and clandestine insertions into food and water supplies, as the RSA apparently never quite mastered delivery systems for CBW agents – though this is disputed and will be covered later.

Each of the four major belligerents in these various interconnected conflicts, Portugal, Rhodesia, the RSA and the Soviet Union and its proxies, will have their possible or actual CBW usage in southern Africa described below. It is important to note that, except for a few highly disputed incidents that will also be covered, CBW use in these conflicts were almost always of an unconventional nature. These include poisoning of water supplies, assassinations, and distribution of contaminated food and clothing to insurgents, as opposed to the more traditional chemical rounds delivered by artillery. These types of usage make classification of the chemical weapons difficult, as they do not fall in line with the traditional first, second, third or fourth generation nomenclature traditionally used to classify battlefield chemical weapons.[24]

Portuguese CBW Usage

> *"The United Nations is useless . . . and also harmful."*
> *– Portuguese dictator Antonio de Oliveira Salazar*[25]

Portugal's attempts to maintain control over its colonial possessions were noted as particularly brutal, although repression of the press often meant Portuguese themselves knew little about what occurred during these wars.[26] Massacres of civilians by Portuguese forces in Mozambique in particular were distressingly common, most infamous of which was the Wiriyamu massacre, in which Portuguese security forces massacred 400 civilians in retaliation for a FRELIMO attack which inflicted six casualties on Portuguese soldiers in 1972.[27] Portugal's actions in Mozambique were so egregious that UK Labour Party Leader Harold Wilson described them as part of an overall Portuguese policy of genocide with "no parallel . . . since Nazi times."[28]

These massacres overshadowed a more insidious means of eliminating opposition, specifically CBW. While not used via delivery systems on the battlefield, Portugal would poison prisoners of war and, allegedly, poisoned water supplies.[29] Furthermore, in Mozambique, Portugal followed a process similar to the "strategic hamlet" concept that the U.S. used in Vietnam, though multiple Catholic missionary sources state that such hamlets were intentionally undersupplied with health services and the population underfed to foster disease to kill potential FRELIMO supporters and "let as many Africans as possible die," with many of the hamlets (known as aldeamentos) compared to Nazi death camps in the official UN report.[30]

Contrasting with Mozambique, Portugal instead used herbicides extensively as weapons of war in Angola, as a way to circumvent a U.S. arms embargo on "all arms for use in Africa."[31] While herbicides are not technically considered chemical weapons, their use would subsequently be banned by the 1978 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques.[32] In 1970, only three countries would vote against an international treaty banning herbicidal use in war – Australia, the United States, and Portugal.[33] Whether intentional or accidental, herbicides also made their way into water supplies and poisoned both civilians and insurgents.[34]

Rhodesian CBW Usage

> "The more we killed, the happier we were. We were fighting terrorists."
> – former Rhodesian Prime Minister Ian Smith[35]

Rhodesia is an excellent example of how tactical superiority is not the best measure by which to determine the outcome of a war. Between 1966 and 1972, Rhodesian security forces killed 300 guerrillas and captured an additional 500 while suffering only 14 soldiers killed in the same time period.[36] Rhodesia habitually relied on statistics for total insurgents killed while ignoring the broader political context in which it existed. This is exemplified by its adoption of a CBW program, which was extremely effective against insurgents but only further isolated Rhodesia and hardened resolve against the government. Rhodesia could never win the hearts and minds of its populace, for it was a government specifically for a privileged few over the masses. The Rhodesian government relied on force and brutality, but as it lost the support of its few allies and black Rhodesians who came identify more with the insurgents over government forces, it became evident that while Rhodesia probably would not lose the war, they definitely could not win it.

With Portugal's withdrawal in 1975, the Mozambican border opened a new front in the Rhodesian war, which made it significantly easier for ZAPU and ZANU insurgents to escape to foreign hideouts and reorganize. As Rhodesia's security situation became more untenable, the Ministry of Defence began, in the last quarter of 1974, to work with toxicologist Robert Symington to develop a CBW program.[37] Poisonings of clothing, food and medicine began in 1977 and did not end until the conclusion of the war in late 1979, though the first possible use of CBW were cholera outbreaks in 1973.[38] Biological agents utilized include cholera, anthrax and perhaps botulinum, and chemical agents included thallium, parathion (a nerve agent), telodrin, and warfarin.[39] The Rhodesian Medical Directorate at Army Headquarters stated they were researching a means by which to identify organophosphate poisons in water supplies to protect their own troops from insurgent poisonings, but this is more likely to have been a cover to hide the fact that water supplies poisoned by security forces would subsequently accidentally be used by different Rhodesian units and cause casualties to friendly forces.[40]

The Rhodesian CBW effort amply demonstrates that internationally isolated regimes can produce significant quantities of chemical and biological weapons if they are sufficiently dedicated. Agricultural and industrial chemicals provided cheap alternatives to typical conventional chemical weapons, and particularly when used in individual assassinations and poisonings can be horrifically effective.[41] Further masking the extent of the biological component of Rhodesia's program is the potential use of viruses naturally occurring in the region, such as cholera and anthrax, which masked intentional use and still to this day leave questions as to natural or man-made intent on several outbreaks. Even though the existence of the Rhodesian CBW program is confirmed without a doubt, there is a severe paucity of primary sources as most were apparently destroyed or did not exist in the first place. Limited documentation portrays definitive Rhodesian security force usage of poisonings, and insurgent commanders frequently feared poisonings and other unconventional operations against them.

Nicholas Nkomo, a commander in the Zimbabwe People's Revolutionary Army (ZIPRA, military arm of ZAPU), stated that the Rhodesian CBW program was the most effective strategy deployed against his troops by the Rhodesian government.[42] The CBW program was largely run by the Rhodesian Central Intelligence Organization (CIO), with many specific instances of poisonings and attacks attributed to the Selous Scouts, a special forces unit that worked directly for the Special Branch (a part of the CIO) rather than the military. The Selous Scouts would also insert cholera into water supplies, disseminated contaminated clothing to insurgents, and poisoned wells, leading to hundreds if not thousands of civilian deaths in addition to insurgent casualties.[43] The Selous Scouts were responsible for 68 percent of all insurgent kills and captures in the areas they operated in, far surpassing any other Rhodesian combat unit.[44]

The total number of guerrillas and civilians killed by the Rhodesian CBW program is the subject of much debate, with figures ranging from around 800 to over 3,500; this does not factor in hundreds of Mozambican civilians who may have also drank contaminated water, or "friendly fire" incidents when security forces unwittingly drank from previously-poisoned supplies.[45] For a war with a total estimated casualty figure of 20,000 people, this is a significant quantity whose deaths were attributed to the CBW program, even with the conservative estimate.

RSA CBW Usage

> *"The free world wants to feed South Africa to the Red Crocodile [communism], to appease its hunger."*
> *– RSA Prime Minister P.W. Botha*[46]

The RSA's CBW program was known as Project Coast and was initially developed due to fears of the Soviet Union providing Cuban and Angolan forces with CBW.[47] Despite protests that the program was initially solely based on defense against CBW, it is apparent from previously top secret SADF documents that offensive use of CBW was part of the program from the start.[48] Furthermore, despite protests that Project Coast only began in response to alleged Cuban use of chemical weapons, Project Coast began in 1981 and the first alleged Cuban chemical attack was in 1984.[49] In all likelihood, much like the RSA's nuclear weapons program, Project Coast most likely came about due to the RSA's feeling of betrayal after their CIA-supported incursion into Angola in 1975, which was subsequently condemned overtly by the US government. The U.S. banned military aid to the RSA shortly thereafter.[50] Seeing themselves almost alone against the Soviet Union and its allies, the RSA sought weapons of mass destruction to even the odds, stating in an official order to the entire SADF that "the best manner to prevent chemical or biological weapons use against a country is to have similar capabilities that credibly can be applied during retaliation."[51]

Confusion underlined SADF doctrine on usage of chemical weapons, in that they were potentially useful because "[c]hemical weapons . . . provide the user with the advantage that specific military and political goals can be achieved before such action can provoke international resistance.[52]" This is due to the ambiguity of detecting and properly identifying the source and cause of a chemical attack, which is illustrated by the fact that it is still inconclusive if there were chemical attacks in Angola and, if so, by whom, over 30 years after the war ended. Furthermore, the value of propaganda regarding CBW cannot be understated; it seems that unsubstantiated Soviet and Angolan claims of chemical warfare attacks by the RSA at the battle of Cuvelai in 1984 were propagated primarily to excuse the atrocious performance of the 11th Angolan Brigade and its SWAPO allies that were destroyed in that conflict while only killing seven RSA soldiers in return.[53,54]

The RSA held its numerous African enemies in contempt – though they highly respected Soviet and Cuban forces – as evidenced by this excerpt from the RSA's policy on CBW, which also tacitly admits that CBW had been used by the RSA in some form:

> *"Hierbenewens hou die aanwending van chemiese wapens teen primitiewe of bygelowige volkere die voordeel in dat dit aan die bo-natuurlike toegeskryf kan word." [translation: In addition, the application of chemical weapons against primitive or superstitious peoples holds the advantage of them attributing [the effects] to the supernatural].[55]*

Apart from the diary of Igor Zhdarkin, a Soviet advisor to the Angolan army, who states that the RSA used chemical weapons delivered via artillery against the Angolan 59th Mechanized Brigade in October 1987 at the Battle of the Lomba River,[56] there is no primary source evidence of the RSA's use of chemical weapons on the battlefield. Zhdarkin had a very low opinion of the Angolan troops he was attached to, but even so the single reported usage of chemical weapons makes no tactical sense as RSA conventional artillery were dominating the battle, with all four Angolan brigades participating suffering 60-70% casualties.[57] Deception also played a role in the RSA's CBW program, and this may have confused Zhdarkin. Efforts were made to convince the Cubans and Soviets that the SADF was deploying chemical weapons on the battlefield which in reality were simply colored smoke, as "signs of a chemical warfare attack . . . would force the Cuban and Angolan forces to don [chemical] suits, which would cut combat effectiveness in half.[58] Given the disparity in force size, as the SADF was almost always outnumbered by Cuban and Angolan forces, deception operations mimicking chemical attacks were considered to be a force multiplier, though actual instances of this are difficult to identify.

The only other credible allegation of CBW use was in Mozambique in 1992, when a FRELIMO patrol may have come under chemical attack. The South African Truth and Reconciliation Commission, which was established to identify human rights abuses under apartheid, investigated and, after reviewing reports from five different scientific teams, was unable to conclude whether chemical weapons were used as the results were inconclusive.[59] Regardless of definitive facts, Cuban forces believed the RSA possessed nuclear and chemical weapons and troops were issued gas masks and protective gear – though, oddly, this very gear is what convinced the RSA that it was Cuba and the Soviet Union that planned to CBW.[60]

While RSA use of CBW on the battlefield is at best inconclusive, there is no doubt whatsoever of CBW internally against domestic opponents. The development of agents was twofold – many were produced for political assassinations, while another branch worked on riot control agents to, as former SADF chief Constand Viljoen put it, "calm people down, make them friendly, if at all possible," to avoid "another Sharpeville [massacre] where my forces would have to kill people to bring them under control."[61] The branch working on political assassination was significantly more prolific.

One of the most damning documents proving South African's program was used to kill dissidents is the "Verkope Lys" [Shopping List] found in a trunk owned by Wouter Basson, head of Project Coast, with toxins used for poisonings and their known uses in Table 1 below. This is just a small subset in a period of time in 1989 as to what poisons and bioweapons were available for use by security forces. Known biological organisms that Project Coast researched included "anthrax, cholera, salmonella, botulinum . . . E. coli . . . necrotizing fasciitis, hepatitis A, and H.I.V. . . . and the Ebola, Marburg, and Rift Valley hemorrhagic-fever viruses."[62]

Sales List			
Date Delivered	**Substance**	**Volume**	**Notes**
3-Mar-89	Phencyclidine (PCP)	1 x 500 mg	odorless pesticide
23-Mar-89	Phencyclidine (PCP)	5 x 100 mg	PCP given to psychologist Johnny Koortzen
4-Apr-89	Aldicarb in orange juice	6 x 200 mg	Pesticide, possibly given to SWAPO POW in Namibia
4-Apr-89	Azide in whiskey	3 x 1.5 g	1.5 g of azide is almost double the fatal dose
4-Apr-89	Paraoxon	10 x 2ml	Pesticide, fatal dose as little as 1/50th of a teaspoon
7-Apr-89	Vitamin D	2 g	Rodenticide, nonlethal but effects are debilitating
15-May-89	Vitamin D	2 g	Rodenticide, nonlethal but effects are debilitating
15-May-89	Cantharadine	70mg	Biological poison from beetles, lethal dose 10mg, given to unnamed policeman
16-May-89	10 ml syringes	50	
16-May-89	Needles 15G x 10mm	24	
19-May-89	Needles 17G x 7.5mm	7	
30-May-89	Thallium acetate	1 g	Colorless, odorless pesticide
9-Jun-89	Phosphide tablets	30	Upon contact with moisture or swallowed, releases poisonous gas phosphine
20-Jun-89	Envelope laced with spores (anthrax)	1	Placed on gum of envelope to get the target to ingest spores
21-Jun-89	NaCN capsules	50	Target medications would be replaced with NaCN capsules to poison them, given to individual known only as "Koos"
21-Jun-89	Beer bottle with botulinum	3	Most poisonous biological toxin known to exist, 1 million times more poisonous than arsenic
21-Jun-89	Beer bottle with thallium	3	
21-Jun-89	Beer bottle with botulinum	1	Most poisonous biological toxin known to exist, 1 million times more poisonous than arsenic
22-Jun-89	Beer bottle with thallium	2	
27-Jun-89	Salmonella typhimurium in sugar	200g	Microogranism which causes typhoid fever
20-Jul-89	Paraquat in whiskey	1 x 75ml	Herbicide, fatal dose 15ml
27-Jul-89	Hg-cyanide	4g	Mercuric oxycyanide, poisons by both mercury and cyanide poisoning, given to man known only as "Koos"
3-Aug-89	Baboon fetus	1	Hung outside residence of Archbishop Desmond Tutu, either as a threat or attempt at biological warfare

Table 1a. "Shopping List" provided by Roodeplaat Research Laboratories (RRL) for covert assassination missions in 1989, adapted from a table and multiple paragraphs from United Nations Institute for Disarmament Research Report on Project Coast, with translations from Afrikaans by Marizel Mihal[63]

Sales List			
Date Delivered	**Substance**	**Volume**	**Notes**
10-Aug-89	Vibrio cholera	16 bottles	Organism which causes the disease cholera, to be dumped in water supplies
11-Aug-89	Azide 4g	7 capsules	
11-Aug-89	Cigarette with anthrax	5	
11-Aug-89	Coffee chocolate with anthrax	5	
11-Aug-89	Coffee chocolate with botulinum	5	
11-Aug-89	Peppermint chocolate with aldicarb	3	
11-Aug-89	Peppermint chocolate with brodifacoum	2	May have been tested on POW in Namibia
11-Aug-89	Peppermint chocolate with cantharadine	3	
16-Aug-89	Peppermint chocolate with cyanide	3	
16-Aug-89	Vibrio cholera	6 bottles	Organism which causes the disease cholera, to be dumped in water supplies
16-Aug-89	Sodium cyanide capsules	7	
18-Aug-89	Formalin and pyridine	30 x 50ml	
18-Aug-89	Needles 10cm x no 16	12	
5-Sep-89	Cantharadine powder in sachets	100mg	
8-Sep-89	Methanol	3x30ml	Becomes formaldehyde and formic acid in the liver when ingested, lethal poison
8-Sep-89	Vibrio cholera	10 bottles	Organism which causes the disease cholera, to be dumped in water supplies
8-Sep-89	Snakes	2	Possibly mambas, see below
8-Sep-89	Mamba toxin		Amount unspecified, the mamba is a dangeous venomous snake
13-Sep-89	Digoxin	5mg	Fatal dose 5mg, used in botched assassination attempt on ANC leader Dullah Omar
18-Sep-89	Whiskey 50ml + colchicine	75mg	Fatal dose 10mg, given to unnamed policeman
6-Oct-89	B. melitensis c	1 x 50	Causes brucellosis, given to unnamed security operator
6-Oct-89	Salmonella typhimurium in deodorant	1	Microogranism which causes typhoid fever
11-Oct-89	Cultures for letters (anthrax?)	2	
21-Oct-89	B. melitensis c		Causes the disease brucellosis
21-Oct-89	Salmonella typhimurium in deodorant	1	Microogranism which causes typhoid fever

Table 1b. "Shopping List(Cont)" provided by Roodeplaat Research Laboratories (RRL) for covert assassination missions in 1989, adapted from a table and multiple paragraphs from United Nations Institute for Disarmament Research Report on Project Coast, with translations from Afrikaans by Marizel Mihal[63]

The first recorded use of CBW by South Africa is the use of scoline and tubarine to assist in the execution of "hundreds" of SWAPO prisoners beginning in 1979 to handle overcrowding in prisons.[64] There was little to no oversight of the Civil Cooperation Bureau (CCB), the organization that handled most political assassinations in the late apartheid era, and this led to many bizarre, brutal ideas being put forth. Activities ranged from the nefarious, such as sending HIV-positive security force members to brothels known to be frequented by insurgents in the hopes of spreading the virus[65] and the attempted development of a "black bomb," a virus that would only infect black South Africans and not whites,[66] to the faintly ridiculous, including leaving poisoned razorblades in the office of an anti-apartheid lawyer in the hopes that he would use the blades to shave, cut himself, and die of blood poisoning.[67]

In the chaotic near-civil war between the ANC and Inkatha following the legalization of the ANC, security forces would use the opportunity to settle scores with the insurgents by acting as a "Third Force," in the conflict. Simultaneously, Project Coast took decidedly more illegal activities, including drug production and distribution, including ecstasy and mandrax.[68] Assassinations of all sorts proliferated, from bombings, shootings, stabbings, and poisonings, until the election of 1994.

Soviet Union and Proxy CBW Usage

I'm sure the Cubans will go ahead with this. This is the new military tactic."
– discredited toxicologist Aubin Heyndrickx[69]

There are repeated allegations of Soviet/Cuban/Angolan chemical weapon use against the RSA and UNITA, to include the following allegations by UNITA as reported by Physicians for Civil Defense in 1990:

"According to UNITA military intelligence leader General Peregrino Wambu Chindondo, chemical weapons used by Soviet-supported forces have caused 83 cases of severe respiratory distress, with 38 fatalities. Paralysis occurred in 293 persons, leading to death in 42. Dr. Manassas, director of the UNITA hospital in Jamba (the capital of ``free Angola''), noted that medications that in early cases brought improvement or relief increasingly either lost their effectiveness or actually worsened the patient's symptoms.

A captured soldier told of being trained in chemical warfare by Cuban specialists. [Chemical] Testing kits exactly like those taken from Soviet soldiers in Afghanistan were found.

UNITA claimed to have discovered a large cache of Soviet-made chemical weapons in Luanda, presumably intended for a massive offensive with chemical weapons, against which UNITA would have been defenseless. As a result of this information, Savimbi acquired 20,000 gas masks.

Andreas Holst, a German, recovered bomb fragments with Russian inscriptions, which on testing in Ghent revealed cyanide-containing compounds. Tests carried out by Belgian toxicologist Aubin Heyndrickx were confirmed in a parallel investigation in a British laboratory."[70]

However, a CIA report issued in 1989 and declassified in 2013 disputed these findings, stating that there was no evidence of lethal CBW agents used in Angola, attributing the illnesses to consumption of improperly prepared cassava plants, an abundant food in the region.[71] Raw cassava contains cyanide, though it seems odd that guerillas who lived in, and subsisted primarily on, cassava plants wouldn't know how to prepare it.[72] An additional counter-argument to RSA claims of Soviet or Angolan use of chemical weapons against UNITA in 1989 is that it may have been a field test of an RSA delivery system that went awry and struck UNITA troops instead of the enemy.[73]

What further weakens the case of Cuban or Soviet use of chemical weapons in Angola is the fact that University of Ghent toxicologist Aubin Heyndrickx was the only individual to ever put forth these claims, and he is a problematic source at best. Evidence demonstrating that Heyndrickx had financial and personal links to Project Coast's Wouter Basson would come to light after he made CBW allegations against Cuban forces in 1988. A second blow would come when the dean of his own pharmaceutical faculty described his reports on CBW use in Angola as "unsubstantial and useless."[74] Finally, and perhaps most fatally to his findings, Heyndrickx was convicted of falsifying lab results and subsequently expelled from the University of Ghent in 1995.[75] All of these factors point to Heyndrickx being a deliberate source of disinformation, either to justify Project Coast's existence or to provide cover for its activities by muddying the waters as to who used CBW in Angola, if they were used at all.

The most curious case of disinformation in the context of chemical warfare was the career of Soviet Lieutenant-General Konstantin Shaganovitch, a chemical warfare officer who was placed in charge of all Cuban, Soviet and Angolan forces. Shaganovitch was so well-known that the final Anglo-Cuban offensive of the war and subsequent battle of Cuito Cuanavale in 1987 was termed "The General Shaganovitch Offensive" by British war correspondent Fred Bridgland.[76] Numerous books and articles mention him, and General Shaganovitch was even discussed in the British House of Lords in a debate over what British policy should be in Angola.[77] General Shaganovitch's assignment was seen as proof that the Soviet Union intended to use chemical weapons against the SADF; after all, why else would the Soviet Union give operational command to a chemical officer?

There was just one issue with this speculation: General Shaganovitch did not actually exist.[78] Whether intentionally or not, it seems that "Konstantin Shaganovitch" was both a combination and mis-transliteration of the names of two different Soviet generals assigned to head the Angolan mission, neither of whom were chemical warfare specialists: Lieutenant-General Vassily Shakhnovich and Lieutenant-General Konstantin Kurochkin. Both of these men had since left Angola by the time of the 1987 offensive. The Soviet commander at the time of the offensive was actually General Petr Gusev.[79] Whether this confusion was a means by which South Africa sought international aid and condemnation of its Soviet and Cuban adversaries, or a mistake by over-eager intelligence analysts, may never be known, though discussions of the fictional general continue to plague accounts of the Battle of Cuito Cuanavale.

Finally, the Rhodesian government was not the only organization to use poisons in its war against ZANU and ZAPU, as the insurgent groups themselves planned and may possibly have done the same thing. An early plan, apparently never carried out, involved poisoning a water source used by "Europeans" with arsenic, and the Shona (a Zimbabwean ethnic group) had a rich heritage of herbalism and using poison, which apparently extended to after the war's conclusion.[80] Finally, an alternative explanation to the anthrax outbreak of 1978-1980 was not that it was caused by Rhodesian security forces, but was part of the internal struggle for power between ZAPU and ZANU as the war came to a close with an insurgent victory, and this was the reason the Zimbabwean government has not pushed for a stronger investigation into the event.[81]

Conclusion

We were literally taught to hate. If you look at the security course I went on, for five weeks we were subjected to, and we swallowed all of this, the ranting and raving of a person that I'll describe as a cross between Hitler and Eugene TerreBlanche [leader of the Afrikaner Weerstandsbeweging - AWB (Afrikaner Resistance Movement), a South African neo-nazi group)]. About the satanic, godless Communists and their black surrogates that were going to swamp us. Officially we were taught to hate. It was a culture of hatred." – Warrant Officer Paul Erasmus, classmate of Eugene de Kock, founder of Koevoet and commander of the C10 counter-insurgency unit[82]

Countries that are internationally isolated already, just as South Africa was and North Korea is currently, can lead such countries into examining any means necessary for their survival, and they will attempt to inculcate that "survival by any means necessary" mindset in their population. Small-scale chemical and biological weapons use can be notoriously difficult to detect, which makes them attractive options to governments facing internal insurgencies. While continued emphasis on identification and destruction of chemical weapons stockpiles, such as in Syria, are admirable and necessary, they are a relatively easy goal compared to facing programs such as the ones South Africa and Rhodesia employed. Recent years have seen an uptick in CBW use in assassinations by countries such as Russia and North Korea, and these types of programs are significantly more difficult to detect and prevent than conventional battlefield use. Despite robust international condemnation and embargoes, Rhodesia, South Africa and North Korea all independently developed and fielded significant quantities of weapons of mass destruction. The parallels are obvious and disturbing.

Even when the use of CBW is overt, the lack of strong condemnation and actual consequences for the use of CBW degrades the deterrent value the international community has against their use. CBW use in Africa has received barely any attention from the international community, and this emboldens those who would use these weapons in future conflicts. The low cost and relative secrecy involved in their use when employed correctly means that many states may continue to look to CBW, particularly against internal insurgencies or political enemies.

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Estimating Operational Internal Dose from Predicted Localized Fallout

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Introduction

The internal dose rate hazard from fallout generated by a near-surface nuclear detonation has been computed using International Commission on Radiological Protection (ICRP) Publication 119 inhalation dose coefficients and the Defense Land Fallout Interpretive Code (DELFIC) fallout modeling code as incorporated into two Oak Ridge National Laboratory (ORNL)-maintained nuclear forensic mission planning tools. Incorporating internal dose contributions from a full intersection of isotopes present in both ICRP 119 and DELFIC's modeled isotopic inventory, the potential ratio of simulated internal to external dose rate contributions was on the order of 10^{-3} or less within the time and spatial domain of forensic interest. The results indicate that the internal dose hazard can be reasonably ignored as an operational planning factor during nuclear forensic ground collection missions, even when employing conservative assumptions regarding resuspension and inhalation efficiency across the modeled particle size distribution.

Background

In the immediate aftermath of a near-surface nuclear detonation, an enormous quantity of material entrained into the rising fireball will be intermixed with fission products generated during the explosion and lofted up to tens of kilometers into the atmosphere. This fallout, distributed via a combination of particle settling and atmospheric transport, can pose a significant and possibly lethal external dose risk in areas near to ground zero (GZ) and the ability to accurately model this surface deposition must be a high priority for any hazardous material dispersion codes which intends to model nuclear weapon effects.[1,2] Prominent fallout modeling tools used within the Department of Defense, such as the Defense Land Fallout Interpretive Code (DELFIC), make no attempt to predict the potential internal dose hazard from this distribution of radioactive material, even when many of the inputs required to at least bound potential internal dose to personnel within the fallout field are generated during the simulation process. This omission has some grounding in both data collected during U.S. atmospheric testing and in modeling studies completed using an early version of DELFIC, supporting the conclusion that the relative magnitude of internal dose due to inhalation of airborne fallout material to external dose due to β-γ radiation from the same material was ~10^{-3} – 10^{-6} depending on the distance from GZ.[3,4] This analysis revisits this topic from the

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perspective of ground collection teams who may be required to enter this fallout field during early times post detonation to obtain nuclear forensic samples of interest. It leverages continued development of DELFIC-based planning tools and a more recent inhalation dose model to determine the operational relevancy of the potential internal radiological hazard given the predicted external dose at a given location and also provides insight into the selection of appropriate respiratory protection so as to minimize the total dose to personnel during a collection mission.

DELFIC Simulation Post-Processing

Adapting the methodology employed by Levanon and Pernick, outputs of the Airborne Planning Tool (APTool) and Fallout Planning Tool (FPTool), two DELFIC-based modeling packages developed and maintained by the ORNL Detonation Forensics and Response Group, were combined to generate spatial distributions of fallout material with isotopic data accessible to support internal dose assessments.[4] The Apple II test shot, a 29 kiloton (KT) tower detonation conducted in 1955 at the Nevada Test Site during Operation Teapot, was used as the basis for the simulation nuclear event and historical weather parameters as air sampling and animal study data were collected against which results could be compared during future work.[3,5] The time domain of interest for dose rate computations was defined as 36 to 120 hr post-detonation (H+36 to H+120). This window was judged by the author and supported by past ground collection exercises to be a reasonable reflection of time bracketing the earliest arrival of an off-site collection team through to the collection of sufficient forensic samples to support full characterization of the event. Given this time domain, submersion or inhalation dose from the passage of the radioactive cloud was not addressed as ground collection personnel would not be present during initial fallout deposition. A visual depiction of the relevant geographic features used to frame this analysis are shown in Figure 1, overlaid over historical off-site plume dispersion contours.

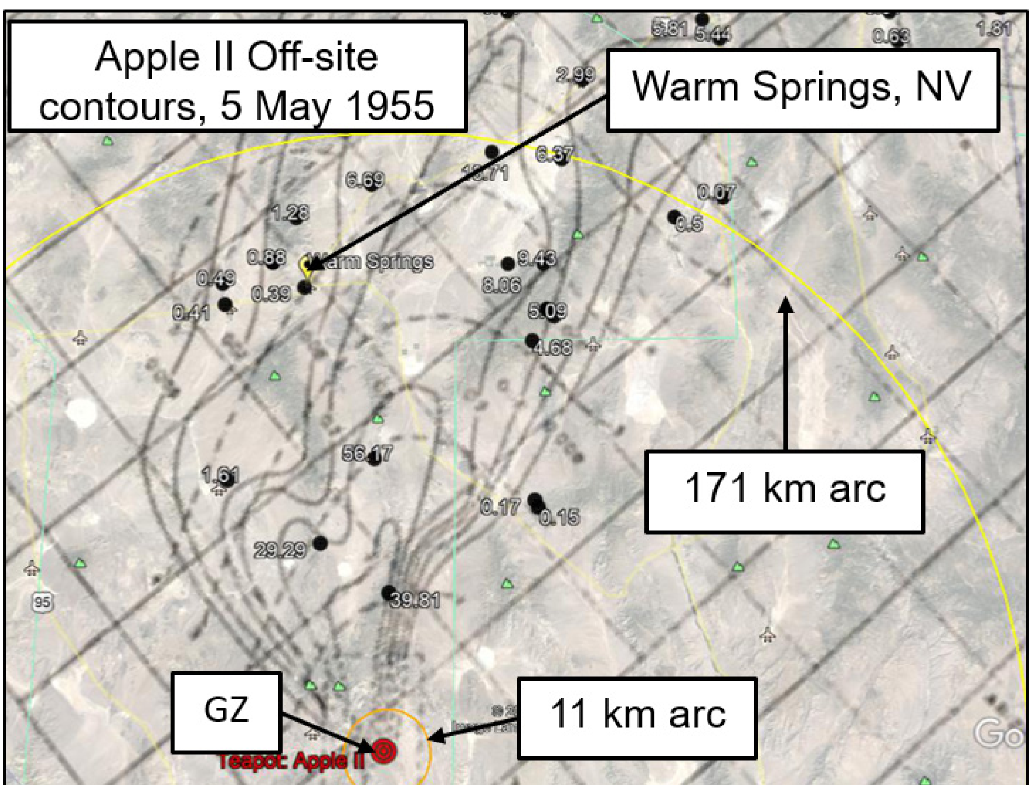

Figure 1. Summary of Apple II deposition pattern and pertinent geographic reference features. Map contours adapted from DNA 1979.[5]

Although both planning tools act as a graphical user interface and intermediate layer to the underlying DELFIC cloud rise source term modeling, in the case of APTool the distribution of radioactive material within the nuclear cloud at time of stabilization is handed-off to the National Oceanic and Atmospheric Administration's (NOAA's) Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT), which computes the more-detailed transport modeling for airborne sample collection applications. This hand-off entails the generation of time-dependent isotopic inventory data, captured in the form of Oak Ridge Isotope Generation (ORIGEN) .f71 files. One inventory file is generated for each of the lognormal particle size classes employed by DELFIC in modeling the cloud rise, with entries at each of the steps in the time domain H+1 to H+121 hours (120 hrs starting at t = 1 hr). Accessing these binary files and formatting them for further analysis required the use of the 'f71tocsv' file conversion utility included in ORNL's SCALE nuclear safety and design code. Setting the distribution parameters to the DELFIC defaults, with 100 particle size classes ranging from a minimum boundary value of 2.584 μm (size class 100) to a maximum diameter boundary of 6.527 mm (size class 1), a full distribution as a function of particle size was then computed for each of the 433 isotopes generated during the cloud rise. Inventory data obtained from APTool provided the necessary insight into fallout composition to determine isotopic distribution from deposition models generated by FPTool. Both DELFIC front-ends use identical source term and cloud rise mechanics, but FPTool computes isotope data in a way not available to an end user via the default interface.[6]

As DELFIC sets particle size class boundaries such that each class has an equal mass fraction of all material distributed within the cloud, specific activity data was computed from the.f71 files after removing isotopes with zero activity across all time steps and particle size classes. Using the mathematical computing language MATLAB (MathWorks, Inc., Natick, MA), the resulting 3-D isotopic inventory data array S_A in becquerels per gram (Bq/g), N isotopes by M time steps by D particle size classes, was combined with ICRP 119 internal dose coefficients to yield a time-dependent weighted isotopic inventory in units of sievert per gram (Sv/g) of intake of material from a specific particle size class

$$S_{DC,i,j,k} = DC * S_{A,i,j,k}, \qquad (1)$$

where S_{DC} refers to the N x M x D specific internal dose coefficient array and DC in Sv/Bq is a vector of dose coefficients applied individually to all entries of the i^{th} isotope in S_A.

The ICRP 119 inhalation committed dose coefficients, based on the ICRP 66 lung model, incorporate fractional deposition as a function of particle size for various compartments within the pulmonary system and addresses limited clearance into the gastrointestinal (GI) tract of inhalable particles which do not penetrate into the extrathoracic region.[7] As an important operational caveat, internal dose coefficients are developed primarily for radiation protection purposes and reflect the committed dose to tissue that would accrue over a full working lifetime (50 years), assuming no post-intake countermeasures to enhance biological removal are employed. The actual rate of internal dose absorbed from any given isotope depends strongly on the effective combination of its radiological and biological half-life. To avoid inadvertently generating internal dose contributions from the incidental ingestion pathway already accounted for by the ICRP 66 lung model, only the inhalation dose coefficients were used to produced specific internal dose factors as a function of particle size class. The 5 μm aerodynamic median activity diameter (AMAD) dose coefficients were selected specifically, as the lower bound of the smallest physical particle size class at 2.584 μm was still larger than the 1 μm AMAD used for the smaller of the two ICRP 119 inhalation dose coefficient categories.[8]

To support fully automated computation of internal dose factors from the DELFIC-modeled time-dependent inventory, AMAD and physical particle size diameter were treated as equivalent quantities and the ICRP 119 lung clearance type yielding the largest dose coefficient for each isotope was used as the basis for conservative internal dose estimates. An upper bound of 100 μm was set as the limit of inhalable particle size, a larger and therefore more conservative size threshold value than used in some previous fallout internal dose modeling studies, with the intake efficiency ϵin as a function of particle diameter dae computed by the American Conference of Government Industrial Hygienists

(ACGIH) sampling efficiency shown in Figure 2 used as a mechanism for modeling the increased contribution of smaller particle size classes to the tabulated internal dose.

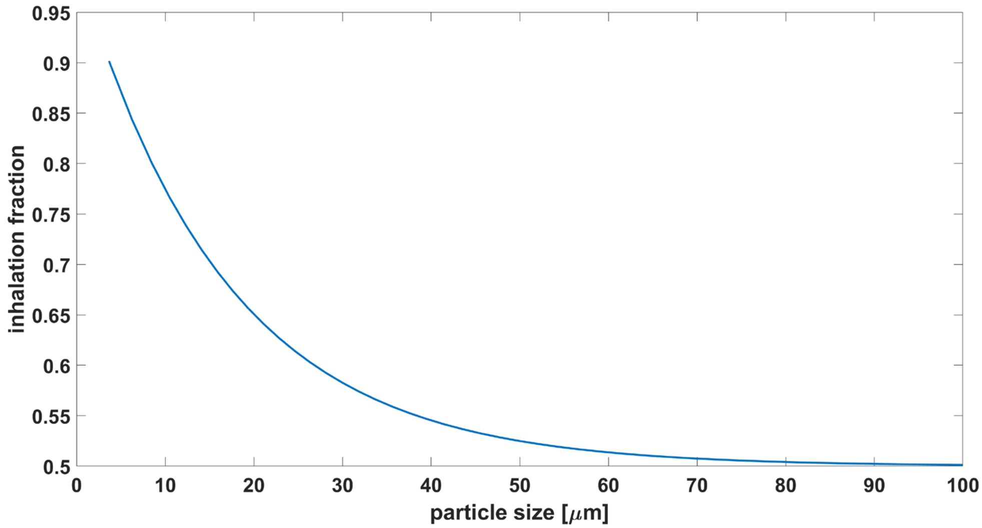

Figure 2. Inhalation efficiency as a function of particle size. Plot adapted from ICRP 66.[7]

Although more detailed pulmonary deposition equations are available, accounting for respiration rate, tidal volume and other related factors, the simplified ACGIH model has the benefit of only depending on a parameter generated during the course of the DELFIC simulation process.[7,9] With this particle size-specific intake, summing over specific internal dose contributions for all isotopes within a particle size class yields DF, a M x D time-dependent specific internal dose factor matrix in Sv/g.

$$DF_{j,k} = \sum_{i=1}^{N} S_{DC,i,j,k} \cdot \epsilon_{in,k} \qquad (2)$$

The dispersion pattern output generated by APTool is geared towards sample collection planning at some distance from GZ, but currently lacks the flexibility and refinement of the ground collection mission tools present in the more established FPTool. Specifically, DELFIC map type 17 (smallest diameter particle) and map type 13 (mass of fallout per unit area in particle size range) contour plots were generated using the documented nuclear event parameters for Apple II to bound the potential internal dose hazard area and to compute an internal dose hazard rate at a given location in the spatial domain. The resuspension factor RF, which is the ratio of airborne radioactivity concentration to surface contamination, is well established as a mechanism to estimate radiological air concentration in cases where only ground deposition data is available.[10] The magnitude of RF varies widely based on the radiological material and environmental conditions in question, with reported values ranging from 10^{-3} to 10^{-9}.[11] Absent an expression for RF as a function of particle sizes in the range used in DELFIC, not found during the literature review for this study, the time dependent model

$$RF = 10^{-6} e^{-\lambda_{res} t} + 10^{-9}, \qquad (3)$$

was used to compute a time-dependent resuspension factor to be applied against all inhalable (≤ 100 μm) particle size classes, although the assumed characteristic decay constant λ_{res} in 1/day was large enough that the *RF* changed very little during the simulation time domain.[11] A fixed respiration rate of V′ = 1.2 m³/hr, the average value for the Reference Worker used as the basis for the ICRP 119 dose coefficients, was then applied to the resulting areal fallout mass concentration M_A in each particle size class to determine the particle-size mass intake rate I′ in g/hr to ground personnel at a given model location.[8]

$$I'_{M,k} = M_{A,k} \cdot RF_j \cdot V' \qquad (4)$$

As a process to automate the extraction of 2-D map array data from FPTool model outputs was not available during this study, the locations of the animal stations used during the Apple II inhalation hazard study were used as control points, although some amount of interpretation was needed to determine map grid locations from the verbal descriptions provided.[3] The internal dose rate at the jth time step $D'_{int,j}$ was then simply the product of *DF* and *I'* summed across k = 100 particle size classes, noting that due to particle settling mechanics only a small fraction of the particle size classes will contribute to the areal density distribution at any given location in the fallout field.

$$D'_{int,j} = \sum_{k=1}^{D} DF_{j,k} \cdot I'_{M,k} \quad (5)$$

Using the Define Routes toolset from FPTool applied against successive map type 3 (exposure rate at H + t) outputs at relevant times of interest, a ratio of internal to external dose rate hazards could then be computed at each sample point to assess the relative magnitude of the contribution. A visual summary of the workflow used in this analysis is depicted in Figure 3.

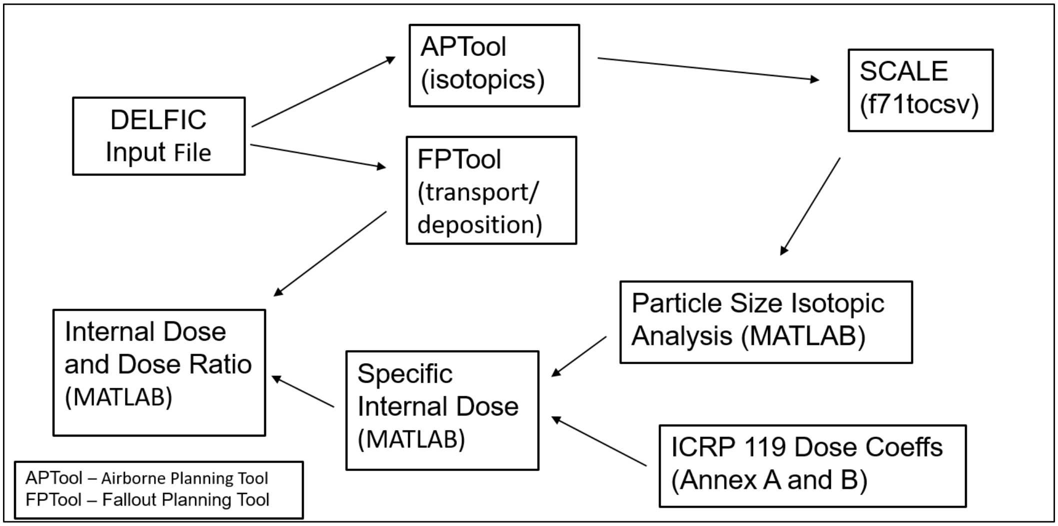

Figure 3. Conceptual framework for estimating internal dose and dose rate from DELFIC modeling output.

Internal Dose Modeling Results

A DELFIC type 17 map, computed over the default Forensic spatial domain of 51.2 km per side with GZ at the origin and 100 m cell size in both the x and y directions, is shown in Figure 4 and provides a telling early indicator of the potential for internal dose hazard to ground collection personnel and the minor extent to which uncertainty in the geographic location of the control points would likely impact the conclusions of this analysis.

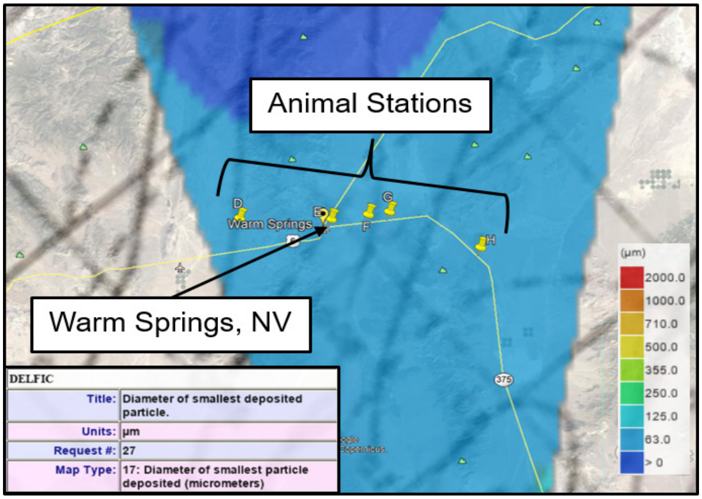

Fig. 4. DELFIC Type 17 map, modeling smallest particle size deposited within (25.6 km)² spatial domain, Apple II test shot, Yield = 29 KT, Height of Burst = 152 m.

Within this area of interest to particulate nuclear forensic collection and analysis, the smallest particle deposited during the DEFLIC dispersion simulation is 194.7 µm, well above the 100 µm inhalable particle threshold. Further simulation runs shifted to FPTool's expanded Consequence Assessment (CA) default spatial domain, increasing by a factor of ten both the grid size length and the total x and y distance.

From the specific activity array S_A, various facets of the isotopic activity characteristics of the inhalable particle size classes were explored, with Figure 5 depicting the time evolution of total specific activity for DELFIC's largest (4.619 mm), smallest (3.652 µm) and aggregate particle size classes, while comparing it to the time behavior of the Way-Wigner external dose rate decay approximation which forms the basis of the seven-ten rule.[1]

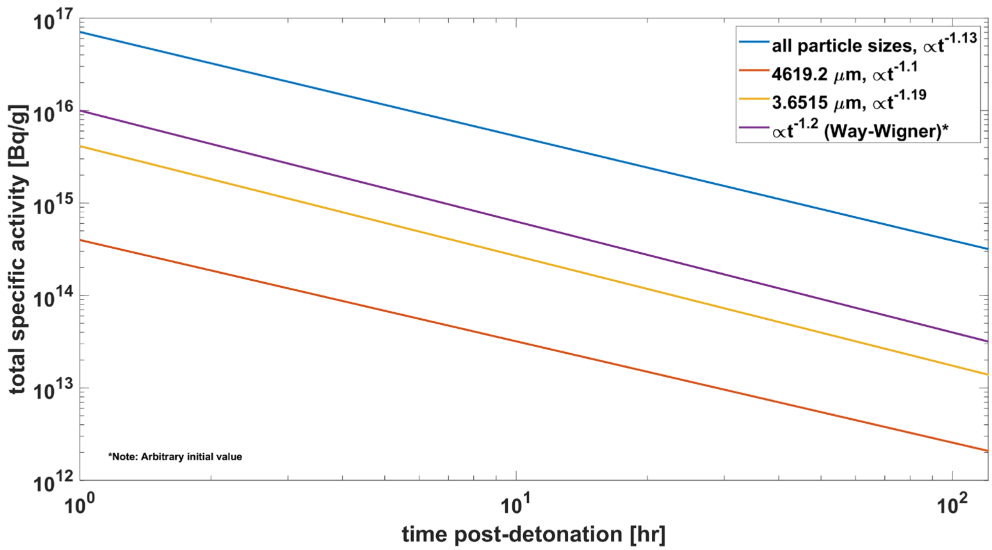

Figure 5. Power law fit to total specific activity as a function of time for select default DELFIC particle size classes.

The extent of fractionation of isotopic activity is shown in Figure 6, both in aggregate and for fallout fission product isotopes identified as of significant health physics interest in previous studies, and in both cases is normalized to activity in the smallest particle size class.[4]

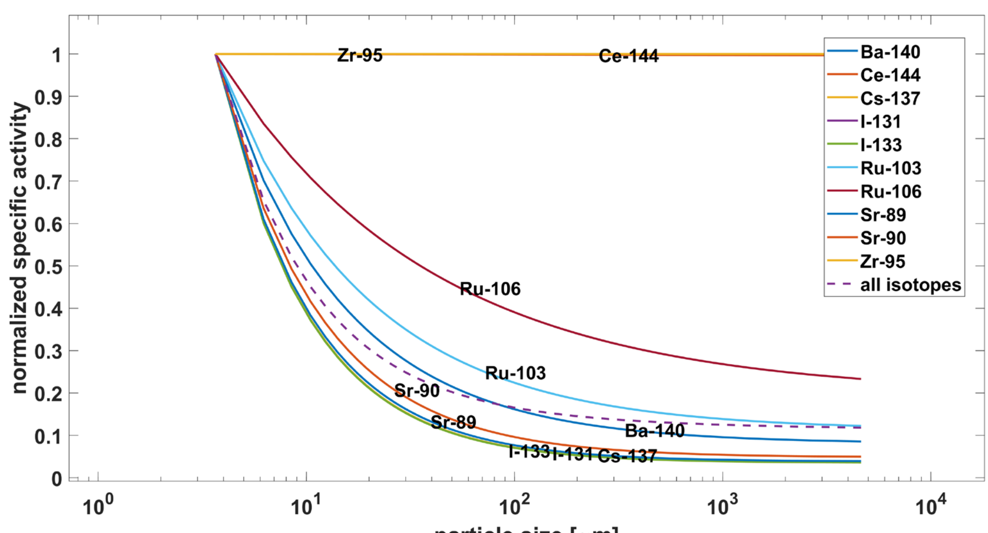

Figure 6. Total specific activity in each DELFIC default particle size class, normalized to specific activity for smallest particle size. Plot for I-133 overlaid on that of I-131.

Applying the computed internal dose rate $D'_{int,\,j}$ to the animal stations used as reference points, Figure 7 completes the analysis by computing a bounding ratio of modeled internal to external dose rate as a function of time, accounting for time of arrival of the fallout at the specific station and the subset of particle sizes deposited at that location.

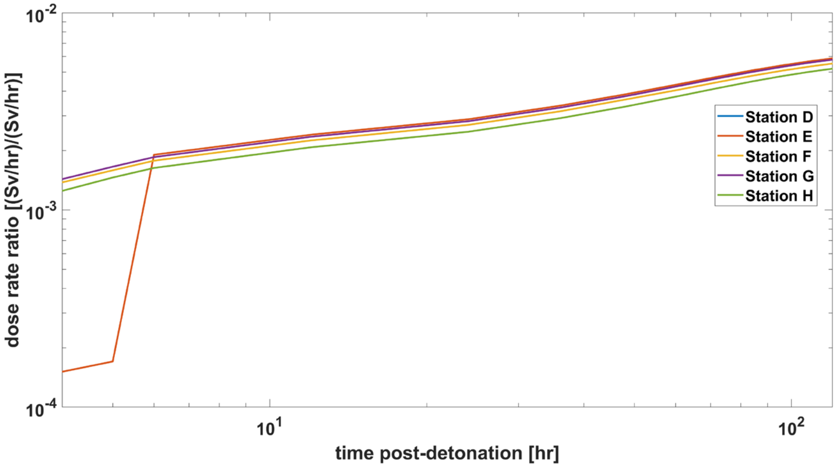

Figure 7. Ratio of modeled internal to external dose rate as a function of time (H+1 to H+121) at animal station reference points, constant respiration rate of 1.2 [m³/hr].

Operational Relevance

As introduced above, the DELFIC map type 17 output is sufficient to address the immediate concern of internal dose rate hazard within the anticipated operational area. In the case of the Apple II-based near-surface burst, fallout of potentially inhalable particle sizes does not begin depositing until around 130 km down-plume from GZ. This settling mechanic provides a multi-layer reduction in the relative internal dose hazard, as turbulent diffusion of smaller particle sizes during transport results in less fallout material available overall for resuspension at these increased ranges. This is especially important given the high fractionation of the medium-lived fission products that may contribute the most to internal dose for a given intake mass, shown clearly in Figure 6. Of the ten fission products of primary interest for internal dose purposes, only Cerium-144 and Zirconium-95 are broadly partitioned across particle size classes and so might expect to make a substantial contribution to inhalation dose for areas nearer to GZ.[4] Only five or six particle size classes contribute to isotopic inventory distribution at any given animal station location, as shown in Figure 8, so only a small subset of the 100 particle size class-specific map 13 outputs are needed to assess the potential internal dose hazard at these reference points.

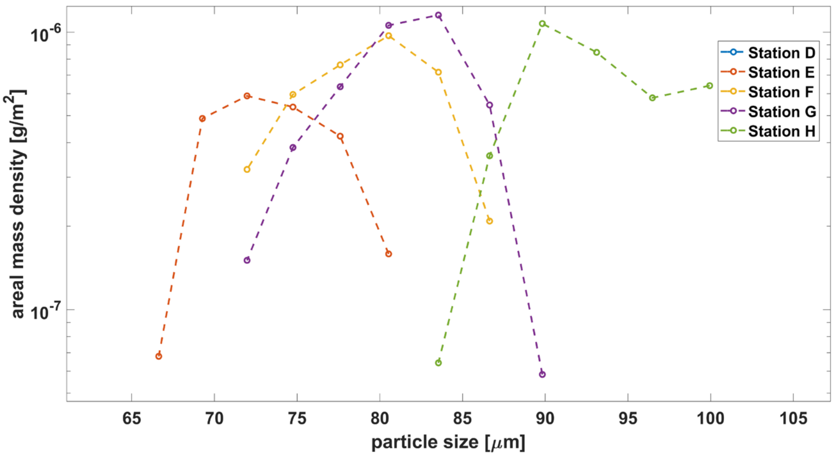

Figure 8. Areal density of predicted fallout as a function of particle size class at animal station reference points.

The time behavior provides some additional insight as to why the internal dose risk relative to the external dose hazard is small during early times post-detonation and might be reasonably ignored as a planning factor. Figures 5 and 7 show at least a rough overall power law dependency with time for all particle sizes within the potentially inhalable size range, even when accounting for isotope-specific internal dose coefficients that depend on biokinetic behavior in the body instead of just radiological properties. The aggregate specific activity computed by the DELFIC isotopic modeling decays faster than the associated external dose rate hazard from the same material, as predicted by the $t^{-1.2}$ Way-Wigner approximation. From Figure 7, the hazard ratio of internal to external dose rate increases with time but with a significant decrease in the total potential dose rate to exposed personnel, incorporating both the internal and external component. By the time this ratio approaches unity, the nature of the radiological hazard has transitioned from acute to long-term. The value ranges of internal to external dose rate, $\sim 10^{-3}$ near the end of the potential mission time-frame, affirm conclusions drawn by previous authors and provides important context in the selection of PPE for any ground personnel tasked with entering the fallout field region during early times. Respiratory protection postures that result in an individual performance decrement and an increased time to complete mission requirements may prove counterproductive, as any committed dose averted by limiting the inhalation of fallout particles would be overshadowed by the increase of external dose due to longer exposure times. A more robust exploration of this topic, examining the impact of yield and height of burst on the relative dose hazard ratio discussed above with a particular focus on the case of a 10 KT surface burst, would provide additional fidelity on the types of nuclear forensic missions in which this risk analysis may be insufficient.

Notes

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Saving Our Own: *Urban Search and Rescue after a Domestic Nuclear Detonation*

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The following article is an adaptation of the master's thesis "Saving Our Own: Maximizing CBRN Urban Search and Rescue Capabilities to Support Civil Authorities", which was published by the Naval Postgraduate School in March of 2021.

Introduction

Following a nuclear detonation in a domestic, urban setting, victims will require rescue from collapsed buildings. In the United States, these efforts fall under the purview of urban search and rescue (US&R), which is defined by the *U.S. National Search and Rescue Plan* as "the location, rescue (extrication), and initial medical stabilization of survivors trapped in confined spaces."[1] Considered independently, conventional US&R operations are highly technical and require advanced levels of skill in rope, confined space, trench, vehicle, machinery, and structural collapse rescue techniques.[2] However, post-nuclear detonation environments present the uniquely combined hazards of secondary collapse, nuclear fallout, and fire to US&R responders, and each must be properly addressed for US&R efforts to be successful after such an incident. Specifically, protection from the hazard of nuclear fallout presents the added complexity of chemical, biological, radiological, and nuclear (CBRN) personal protective equipment (PPE) usage, which limits responder dexterity and vision and requires work/rest cycles, and radiation exposure, which requires the use of stay times.[3] Therefore, emergency response agencies with the potential to perform US&R after a domestic nuclear detonation should incorporate the performance of US&R skills while donning CBRN PPE into their responder training, and they should address the threat of fire and need for large numbers of trained rescuers in their response planning.

"What I'm saying is, if it's possible, you damned well think about it."
-Dr. Jack Ryan in Tom Clancy's *The Sum of All Fears*

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Hazards Presented to Rescuers by Post-Nuclear Detonation Environments

Upon detonation, a nuclear weapon causes a variety of effects, including blast pressure, thermal radiation, ionizing radiation, optical effects, and electromagnetic pulses.[4] These effects can be classified as either prompt or delayed, depending upon when they occur in relationship to the detonation. Certain effects—such as ionizing radiation—exist in both categories. As explained in the *Nuclear/Radiological Incident Annex to the Response and Recovery Federal Interagency Operational Plans:*

> *Nuclear detonations produce 'prompt' effects that radiate outward from the detonation location and 'delayed' effects. Prompt effects usually occur within the first minute after a detonation and include an intense flash of light, blast shockwave, extreme heat, prompt radiation, and Source Region Electromagnetic Pulse. The delayed effects are primarily the neutron-activated debris around the detonation site and the atmospherically dispersed radioactive fallout.*[5]

Figure 1 provides an approximated timeline for the presentation and duration of these effects and their associated hazards following a 10-kiloton improvised nuclear device detonation.

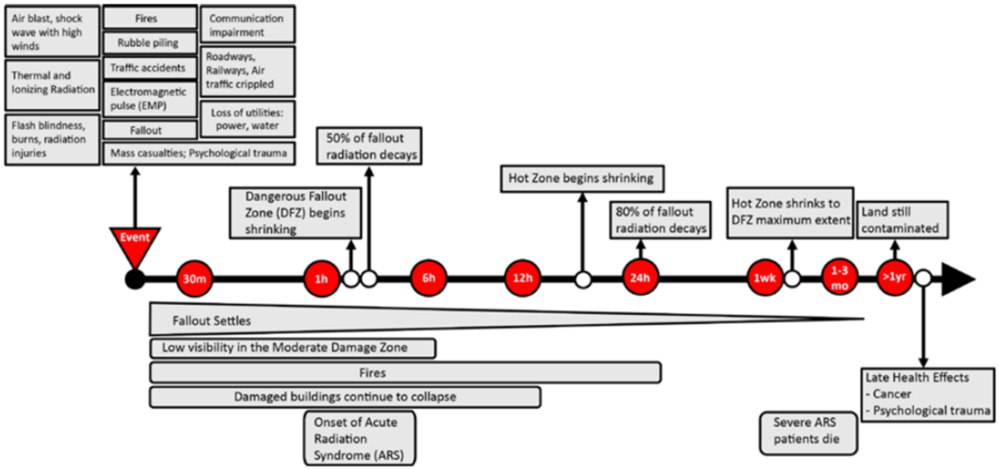

Figure 1. Expected Timeline of Events for a 10-kiloton Improvised Nuclear Device Detonation.[6]

Since they would arrive to the scene well after the detonation, of most concern to US&R responders are the delayed effects and their associated hazards. As seen in Figure 1, these hazards can be defined as secondary structural collapse, nuclear fallout, and fire. In this order, the following section examines each of these hazards through the lens of US&R response.

<u>Secondary Structural Collapse</u>

The prompt effect of blast pressure is what initially causes buildings to collapse and entrap victims, which then requires a US&R response.[7] In the immediate hours after the detonation, the threat of additional, progressive collapse in structurally compromised buildings is also possible, called secondary collapse.[8] However, this phenomenon is a standard, anticipated hazard in any structural collapse emergency, and it is normally mitigated by standard US&R practices, primarily shoring.[9] In the context of a domestic nuclear detonation, it is widespread destruction that can amplify this hazard.

<u>Nuclear Fallout</u>

The effect of ionizing radiation makes US&R efforts in post-nuclear detonation environments particularly unique. According to the Centers for Disease Control and Prevention, "Ionizing radiation is a form of energy that acts by removing electrons from atoms and molecules of materials that include air, water, and living tissue. Ionizing radiation can travel unseen and pass through these materials."[10] This ability to affect living tissue makes ionizing radiation hazardous. At certain dosages, it can cause serious acute and delayed health effects.[11]

Again, since they would arrive to the scene after the prompt effects have occurred, ionizing radiation's delayed effects and associated hazard of radioactive fallout are most precarious to US&R responders. Lingering long after the initial event, this residual radioactive material is found both deposited around the blast site—called groundshine—and suspended in the air, which makes it environmental and atmospheric in nature. While airborne fallout can be spread by wind, making it a significant contamination hazard, groundshine is initially more energetic, making it a greater exposure hazard.[12]

To ensure the health, safety, and operational effectiveness of US&R responders, they must be protected from this exposure and contamination. According to the Department of Health and Human Services' Radiation Emergency Medical Management webpage, "Radiation exposure occurs when all or part of the body absorbs penetrating ionizing radiation from an external radiation source."[13] Conversely, "Contamination results when a radioisotope (as gas, liquid, or solid) is released into the environment and then ingested, inhaled, or deposited on the body surface."[14] Therefore, the time responders spend in radiation fields must be limited, and barriers must be used to prevent radioactive material from contacting and remaining on their anatomies.

Radiation exposure in humans is measured as a dose, and the primary tool for minimizing an emergency responder's dose is the principle of as low as reasonably achievable (ALARA).[15] ALARA calls for minimizing time around, maximizing distance from, and using barriers to shield against sources of radioactivity.[16] Additionally, CBRN incident response agencies should set total dose limits for emergency operations. As an example, the Environment Protection Agency recommends responders not be permitted to receive more than a 25 roentgen equivalent man once-in-a-lifetime dose in lifesaving operations, except on a voluntary basis.[17] Similarly, the National US&R Response System has set a single deployment radiation dose limit of 50 roentgen equivalent man.[18]

Concurrently, US&R responders must be protected from fallout contamination with consideration for the routes of exposure: inhalation, absorption, ingestion, direct contact, and injection.[19] In a post-nuclear detonation environment, this is achieved using PPE. Respirators, eye protection, over garments, gloves, and boots are generally sufficient for a radiation field.[20] However, since collapsed buildings typically present with sharp steel and other injection hazards, US&R work in such an environment calls for more robust, penetration resistant PPE.[21]

<u>Fire</u>

A third, and often less emphasized, hazard to US&R responders following a nuclear detonation is fire. As is the case with ionizing radiation-related hazards, fire is the result of both prompt and delayed effects.[22] In *Whole World on Fire: Organizations, Knowledge, & Nuclear Weapons Devastation*, Lynn Eden describes how the prompt effects of blast pressure and thermal radiation—called nuclear flash—result in fires following a hypothetical 300 kiloton, near-surface blast nuclear detonation near the Pentagon in Arlington, VA. She says:

> *At this [3.5 miles] and greater ranges from the detonation, fire ignitions would result from the tremendous release of thermal energy, which would deposit radiant light and heat on exposed surfaces, causing the simultaneous combustion of many surfaces and structures. Ignitions would also be caused by the breakup of structures from the blast wave and accompanying winds. Structural breakup would cause fires by releasing flammable materials (such as gas, chemicals, and other hazards as gas lines and industrial processes were disrupted), by exposing and shorting electrical lines and equipment, and by exposing additional ignitable surfaces. Such fires are called "blast disruption" fires.*[23]

However, these types of fires are not necessarily uncommon to routine structural collapse incidents. In fact, structural collapse is a common occurrence secondary to large fires in buildings, as is believed to have been the case at the World Trade Center on September 11, 2001.[24] Even in the absence of fire as the impetus, disruptions to utilities and stored hazardous materials create serious fire hazards in most instances of building collapse.[25] In *Fire Department Special Operations*, Retired Deputy Assistant Chief

John Norman of the Fire Department of the City of New York discusses the routine threat of fire in relationship to additional collapse hazards at structural collapse incidents. He warns:

> *While secondary collapse is a major threat, it is not the only danger we face at these events. Fire and explosion are serious threats at any collapse scene, due to the likelihood of ruptured gas and electric lines within the remains of the structure, as well as any occupancy hazards that may be present, such as storage of gasoline, propane cylinders, or other flammables.*[26]

Like nuclear fallout, the phenomenon of mass fire is unique to post-nuclear detonation environments. In *Whole World on Fire*, Eden goes on to describe how delayed atmospheric effects can subsequently result in mass fires following a nuclear detonation. She states:

> *Within tens of minutes after the cataclysmic events associated with the detonation, a mass of buoyantly rising fire-heated air would signal the start of a second and distinctly different event – the development of a mass fire of gigantic scale and ferocity. This fire would quickly increase in intensity. In a fraction of an hour it would generate ground winds of hurricane force with average air temperatures well above the boiling point of water (212°F, 100°C). This would produce a lethal environment over a vast contiguous area. The character of mass fire results from the simultaneous combustion of a large area containing a fuel load typical of a city or suburb.*[27]

It should be noted that scientists and scholars, especially in comparison to blast effects, have passionately debated the occurrence and extent of a mass fire event following a nuclear detonation.[28] As the *Nuclear/Radiological Incident Annex to the Response and Recover Federal Interagency Operations Plans* states, "The likeliness of a firestorm is unknown in an urban environment; some theories suggest modern construction and designs may buffer the fire's ability to grow uncontrollably."[29] Indeed, like any other effect, thermal effects are largely dependent upon a variety of factors. These factors include height of the detonation in relationship to the surface of the earth, energy of the weapon in question, and shielding.[30] Regardless, Eden found that "the uncertainty in the range of damage associated with mass fire can be estimated and modeled, and is not greater than the uncertainty associated with blast damage."[31] Further, she concluded, "For nuclear weapons of approximately 100 kilotons or more, the range of devastation from mass fire will generally be substantially greater than from blast."[32]

Regardless of the impetus, fire effects and their associated hazards must be addressed for US&R efforts to be successful in post-nuclear detonation environments. Even in the absence of a mass fire event, fires secondary to the prompt effects of thermal radiation and blast disruption will burn long after the detonation.[33] As the *Planning Guidance for Response to a Nuclear Detonation* warns, these fires "pose a direct threat to survivors and responders."[34] This threat is especially true for those trapped and operating in collapsed buildings. As Norman points out in Fire Department Special Operations, both rescuer and victim safety and survival depend upon the mitigation of such fires. He states, "At fires that result from explosions or collapses, it is critical to conduct fire suppression efforts simultaneously with rescue efforts."[35]

US&R in Post-Nuclear Detonation Environments

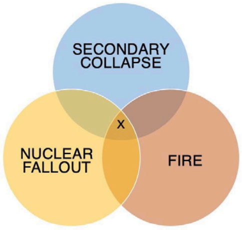

Figure 2. Hazards Presented to US&R by Post-Nuclear Detonation Environments.

As Figure 2 illustrates, the previously listed hazards of secondary collapse, nuclear fallout, and fire must be addressed in concert for US&R lifesaving efforts to be successful after a domestic nuclear detonation. Each presents a life safety threat to both victims and responders that requires appropriate consideration and mitigation. Accordingly, the next segment of this article examines the implications of this unique overlapping of hazards for US&R in post-nuclear detonation environments, particularly on the matter of nuclear fallout-induced radiological contamination.

Urban Search and Rescue in Radiologically Contaminated Environments

Considered independently, US&R is a task-heavy discipline. Mastery requires proficiency in a wide range of skillsets, including rope, confined space, trench, vehicle, machinery, and structural collapse rescue, each of which requires extensive training.[36] Professional firefighters and rescuers often spend years attending courses to obtain the relevant qualifications, and proficiency and expertise is generally built over a career full of responses to real US&R incidents.

Since the discipline of CBRN response is also task-heavy and complex, the threats of radiation contamination and exposure – posed by nuclear fallout – add additional layers of complexity to US&R in post-nuclear detonation environments. In *CBRN and Hazmat Incidents at Major Public Events: Planning and Response*, Dan Kaszeta addresses these added complexities in the general context of radiologically contaminated environments. Towards the end of this work, he presents case studies of "practical scenarios" related to CBRN incident responses and identifies common problems and potential solutions. Scenario M, titled *The "Dirty Bomb" and Structural Collapse*, describes a hypothetical terrorist attack on a large meeting of global financial and political leaders with a radiological dispersal device (RDD). As Kaszeta describes it, "This scenario addresses two potentially overlapping situations, the radiological-dispersal device (RDD)—the so-called 'dirty bomb'—and the possibility of structural collapse, requiring sophisticated urban search and rescue (USAR) methods."[37]

Naturally, it should be noted that an RDD attack is vastly different from a domestic nuclear detonation in both physics and magnitude. An RDD is a conventional explosive device that simply spreads a radioactive contaminant upon its detonation, which makes it much smaller in force and effect than a nuclear weapon.[38] Further, while conventional explosions do have thermal effects, they are usually not nearly as serious or self-perpetuating as nuclear detonations.[39]

Still, Kaszeta's case study addresses the unique, individual challenges presented to US&R efforts by radiologically contaminated environments. He observes, "Structural collapse after a terrorist bombing adds USAR issues to the already complicated issues of postblast investigations and CBRN contamination."[40] He later concludes, "Structural Collapse in a contaminated environment adds a layer of complexity to rescue operations."[41] This complexity is the result of additional considerations that must be accounted for during such a response, including work/rest cycles, diminished dexterity and vision, and stay times.

<u>Work/Rest Cycles</u>

On the matter of simple rescues in CBRN environments, Kaszeta points out, "Rescue is only made complicated in the presence of contamination or of a percutaneous hazard, thus forming an acute hazard to unprotected responders."[42] Nuclear fallout is such a contaminant, requiring the use of CBRN PPE.[43] However, using PPE during periods of high work volume or high stress situations can induce heat stress on responders, requiring frequent rest periods and worker rotations.[44] Planning for these work cycles becomes exponentially complex when the factors of PPE donning and doffing time and decontamination are considered.[45]

<u>Diminished Dexterity and Vision</u>

Additionally, PPE usage significantly reduces responders' dexterity and limits their fields of vision.[46] This reduction is concerning when performing a task-heavy discipline like US&R, which requires fine motor skills and a high degree of situational awareness. According to Norman in *Fire Department Special Operations:*

> *Technical rescue signifies the involvement of a more complex operational environment that often requires specialized tools or equipment as well as a higher degree of know-how to achieve a successful outcome. Another term that has come to signify the tasks involved is Urban Search and Rescue or USAR. The urban environment is where most (but not all, by far) of the more complex accidents occur.*[47]

In the *National Park Service Technical Rescue Handbook*, Ken Phillips agrees by stating that technical rescue work is a very dangerous activity.[48] Mistakes can be fatal, and most are the result of human error.[49]

Stay Times

The final consideration is stay times in radiation fields, which was alluded to in the previous section. According to FEMA, "Stay time is the amount of time a responder is allowed to operate in a radiation field before a predefined dose limit is reached."[50] Above certain doses, radiation exposure can result in acute radiation syndrome, an increased propensity to contract cancer in the future, or death.[51] Therefore, dose limits must be established for US&R responders. By dividing this dose limit by a given dose rate, stay times can be calculated.[52]

Stay times provide timeframes that prevent overexposure of workers operating in radiation fields, as would be the case for US&R in a post-nuclear detonation environment.[53] As FEMA explains, "By knowing this 'stay time' time based on the predefined dose, responders can make a knowledgeable decision about their own safety from radiation, and they can perform their response tasks. In hazardous materials response terminology, this is referred to as 'work mission duration.'"[54] Based upon these stay times, US&R responders should be rotated out of the radiation field and relieved by fresh forces in a post-nuclear detonation environment, as failing to do so could jeopardize their safety and overall operational effectiveness. As Kaszeta explains, "If you do not monitor the accumulated dose of your responders, you may ruin them for future work incidents. Monitor the dose closely and rotate teams to make sure people do not reach their exposure limits."[55]

Recommendations

Because it would be entirely unprecedented and significantly catastrophic, a domestic nuclear detonation would challenge even the best-devised emergency response plans, particularly in the field of US&R. Despite this, many relevant emergency response agencies have failed to adequately address the complexities presented by post-nuclear detonation environments in their applicable planning and doctrine. As Kaszeta points out, "While most USAR efforts acknowledge that hazardous materials of various descriptions may be present in structural-collapse scenarios, not many organizations have taken on the task of both USAR and CBRN concurrently. This area represents an operational-capability deficit in many places."[56] Later, he laments, "This is the area where CBRN/HAZMAT response and urban search and rescue (USAR) converge, and much more work needs to be done in this gap."[57]

To effectively render aid after such an event, this void must be addressed preemptively. To this end, emergency response agencies with the potential to perform US&R after a domestic nuclear detonation should address the added complexities induced by CBRN PPE usage and the threat of fire in their pertinent planning and doctrine. More specifically, they should incorporate the performance of US&R skills while donning full PPE into their responder training, and they should anticipate the need for large numbers of trained rescuers in their response planning.

Perform US&R Skills in CBRN PPE during Training

Currently, outside of certain confined space rescue skills, *National Fire Protection Association (NFPA) 1006: Standard for Technical Rescue Personnel Professional Qualifications* does not recommend that US&R trainees perform technical rescue skills in CBRN PPE during their initial qualification training.[58] However, as previously stated, US&R is a highly technical discipline that requires a high degree of situational awareness, the added limitations on dexterity and vision incurred by these garments notwithstanding. Therefore, rescuers within this mission space ought to be provided with frequent opportunities to practice relevant US&R skills in full CBRN PPE, including during their initial training.

Plan for Fire

While the likelihood of a mass fire event after a nuclear attack is unclear, the widespread presence of fire hazards in collapsed buildings and post-nuclear detonation environments is certain.[59] Although it is not necessarily the role or expectation of collapse rescuers to engage in fire suppression activities, a lack of firefighting knowledge and planning could render US&R responders ineffective. Therefore, rescuers with the potential to respond to a domestic nuclear detonation should be prepared to address the hazard of structural fires. To this end, planning for such an event should anticipate the need for a large quantity of firefighting resources, and US&R responders within this mission space ought to be provided basic structural firefighting training.

Anticipate the Need for Manpower

Finally, responders' exposure to radiation and propensity for heat stress while working for long periods in PPE necessitate the use of work/rest cycles and stay times.[60] As such, the frequent rotation of working personnel makes US&R in post-nuclear detonation environments extremely labor intensive. Therefore, abundant manpower is vital to conducting these operations successfully, and response agencies should anticipate the need for large numbers of trained responders in their response planning.

Conclusion

To successfully rescue victims after a domestic nuclear detonation, rescuers must be capable of overcoming the unique challenges presented to US&R efforts by post-nuclear detonation environments. These challenges include the hazards of secondary collapse, nuclear fallout, and fire.[61] More specifically, mitigation tactics for the hazard of nuclear fallout add the complexities of work/rest cycles, diminished dexterity and vision, and stay times.[62]

However, it should not be assumed that rescuers will be able to perform at an advanced level after a nuclear attack. After all, a domestic nuclear detonation would arguably constitute America's worst day and challenge even the best-devised emergency response doctrine, especially in the realm of US&R. Therefore, emergency response agencies with the potential to perform US&R after a domestic nuclear detonation should incorporate the performance of technical rescue skills in CBRN PPE into their responder training, and they should address the threat of fire and need for large numbers of trained rescuers in their response planning.

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Uranium Enrichment

Clandestine Uranium Enrichment Methods

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Introduction

Since the inception of the atomic era during World War II, scientists have wrestled with the laws of physics to enrich natural uranium to weapons-grade. That struggle has produced many different methods over the past 70 years, the most common being gaseous diffusion or gaseous centrifuge. Both use immense amounts of power and massive facilities to produce poor yields of uranium-235. In the 1970s, a new approach emerged, using a laser to ionize uranium-235 while leaving the unwanted uranium-238 behind. The method, called the Atomic Vapor Laser Isotope Separation (AVLIS), is incredibly power-efficient and produces an extremely high yield of uranium-235 in a short time. [1,2] It is also relatively simple and can be hidden in plain sight at a research facility. The simplicity poses a genuine danger where countries may be enriching weapons-grade uranium without international knowledge or safeguards. Once complete, AVLIS can be used to advance atomic weapons programs without other countries' awareness. This article will prove that AVLIS and its enrichment abilities give any country with the money and expertise the ability to produce highly enriched uranium. Established countries with money and political objectives of this nature are the main threat to a clandestine use of AVLIS to obtain weapons-grade uranium.[3].

Operation

AVLIS operates by vaporizing natural or spent uranium fuel and passing an ionizing laser through the vapor. The laser ionizes the uranium-235 in the vapor, and an electric field is induced to pull the ionized particles to a condensation region. (Figure 1)[2])

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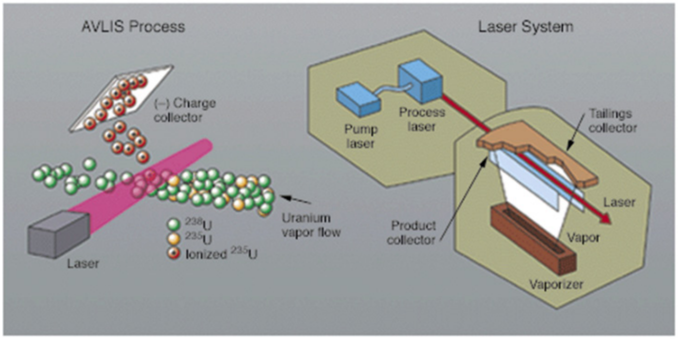

In the laser system used for the LIS uranium enrichment process (right), electrons from the ^{235}U atoms are separated (left), leaving positively charged ^{235}U ions that can be easily collected for use.

Figure 1: Simplified diagram of the AVLIS system [2]

Theories of Operation

Ionization of isotopes

The clandestine use of an AVLIS may be diminishing technological barriers to special nuclear material. Natural uranium is approximately .711% uranium-235. Uranium-235 is a fissile isotope for use in nuclear reactors and weapons, uranium-238 is not useful for reactors or nuclear weapons. The difference in weight causes the electrons of each isotope to have different ionization energies and, therefore, different ionization wavelengths. The difference is caused by the force of gravity between the nucleus and the electrons. The relative size of the isotope plays a role in determining ionization energy. Since the heavier isotope has more neutrons and a larger nucleus, it is closer to its electrons, causing that electron to be held relatively tighter.[6] The actual ionization wavelength for uranium-235 is classified; however, the known range of wavelengths is 500-550 nm.

For AVLIS to operate, there must be selective ionization of uranium-235 isotopes in the vapor. Its wavelength defines the energy of a photon. With a 500 nm wavelength, the energy of the photon emitted by the laser is 2.48 eV. Three photons must be incident on the isotope at once to cause complete ionization due to the required energy of 6.19 eV per atom.[4,5] Once that electron reaches the final energy level, it can escape causing ionization or release its energy and fall back to the ground state. [6]

Required Equipment

Lasers

Since the inception of AVLIS, lasers efficiency has exploded. What used to take up a whole room can now fit in the palm of your hand. [3] The first lasers used for AVLIS were dye lasers. [7] Light is pumped into a reflective box with a particular color dye. Then, once the required energy has built up, the energy is released in a pulse. Dye lasers are very inefficient due to the continuous pulses required to maintain the ionization. Now you can buy a tunable 50-watt laser that meets the same requirements on the open market. [5]

Vaporizer

There are many methods to vaporize uranium; however, using an electron beam gun is best. The electron beam fires highly energetic electrons at the material at an angle between 30 and 60 degrees. [8, 9] The extreme kinetic energy of the electrons is transferred to the target material atoms as heat which causes evaporation. [10]

Vacuum chamber

Creating a vacuum around the uranium vapor is crucial to the operation of AVLIS. Uranium vapor is so highly reactive; it poses severe containment issues. When in contact with the atmosphere, it will immediately bind with the water vapor or corrode when combined with oxygen. [11, 12] If the uranium is allowed to combine with any other atoms or molecules, it will completely change the ionization characteristics, and there will be no enrichment. [3]

Material Handling Requirements

Tantalum and yttria-coated graphite are the only materials that fulfill the requirements to contain the uranium vapor produced during AVLIS. [2] Tantalum is common throughout the world and, therefore, not difficult to obtain. Yttria has similar properties as tantalum, but has some technological barriers. In many cases, yttria is connected to tantalum to gain the qualities of both. However, the combined material is hard to get and strictly controlled.

Expertise Required

There are several fields required to build a successful AVLIS, specifically experts in spectroscopy, lasers, quantum physics, and chemistry. A spectroscopy expert is crucial to ensure that the laser is tuned correctly to ionize the vaporized uranium. Laser experts will need to tune the lasers to specified wavelengths determined by the spectroscopy expert. Quantum physicists will be needed to assist in the determination of the wavelengths as well as determining the power necessary to produce ionization. Moreover, quantum physicists will be needed to build and control the electron beam gun. Lastly, and one of the most critical experts is a chemist. The uranium must remain a consistent atom or molecule so the laser can ionize without needing adjustment.

Clandestine AVLIS Construction

Compared to other enrichment methods, AVILS is the simplest, requires the least amount of components, and requires the least energy. Therefore, the ability of a research university to build such a device is not beyond imagination. Many of the items needed to make AVLIS are entirely available on the open market without trade restrictions. Extremely high-powered lasers, high-powered electron beams, and tantalum/yttria materials are trade restricted. However, there are relatively easy ways around such restrictions. Many other countries do not have the same trade laws as the United States. Any research university or research group can buy many small lasers to do the same work as one large laser to avoid laser restrictions. Furthermore, when asked what a powerful laser is for, Photonics is generally considered a reasonable answer. There is a large market for used lasers not only in the United States but in other countries as well. [15] Once an organization obtains a laser with the specified requirements, building an AVLIS under the guise of research is entirely possible.

To obtain an electron beam is slightly more complex than lasers but still not complicated without raising red flags. Powerful electron beams are used in research all the time. A research organization would have no issues obtaining one. Even if an organization cannot buy an electron beam, it is possible to build one that can meet the requirements of AVLIS. [5] Analogous to lasers, there are many aftermarket electron beams available from many different sources around the world. Lastly, even in the slight possibility that the organization cannot get an electron beam, there are other ways to vaporize the uranium that could take the place of the electron beam, such as an x-ray machine. Obtaining tantalum and yttria have the same issues as electron beams and lasers. However, materials research projects commonly use both because of the unique properties that they possess. Tantalum is sold on the open market in large sheets but is trade restricted by the United States. All other requirements to build a complete AVLIS are of no issue to obtain. This poses a real threat because if a nation is looking to receive unique nuclear material, AVLIS is a relatively easy way to do so. There is much technical expertise required for this device, so a small organization without much money will most likely avoid this process. However, larger organizations like foreign national labs, universities, and research facilities can quickly achieve such a feat. It makes it very difficult to determine whether or not a facility is attempting to build AVLIS because all equipment required for this process is marketable for many other legal research activities.

Observables

A complete AVLIS has very few observables both in its construction and operation. The equipment required, for the most part, will not raise any concern for international trade regulations. Therefore, it is not observable because all the equipment can be used in legitimate research activities. Although many enrichment methods use vast amounts of power, AVLIS uses 5% of the power of gaseous methods for the exact yield. In other words, 84 AVLIS lasers can produce the same amount of enriched uranium in less time than 150,000 centrifuges. [2, 16] Therefore, the power usage is not observable because it is easily hidden within the electronic noise of any actual research. However, AVLIS requires continuous power for many days due to the high enrichment for a small amount of material; however, mass computing and other analysis all require more continuous power usage than AVLIS would.[5,15] The most likely observable is the conglomeration of all necessary experts in one collaborative research organization or facility. However, tracking such experts and equipment will be extremely difficult. There are so many different options to build an AVLIS that chasing the pieces becomes near impossible. Tracking a country's exports in the necessary fields while difficult is more reasonable than tracking equipment. Overall, the observables of a clandestine AVLIS are minimal and pose a threat of enemy states gaining unique nuclear material.

Nuclear Export Controls

There are many controls on nuclear materials. Many different United States Government departments and agencies have a say in export controls and international agencies such as the IAEA. The State Department has a nuclear section in its International Traffic in Arms Regulations (ITAR) and the Commerce Department in its Export Administration Regulation. [18,19] The most precise regulation is found in the Nuclear Regulatory Commission's Part 110, Title 10 Code of Federal Regulations: "Export and import of nuclear equipment and material." [20] It lays explicitly out components and tolerances for nuclear materials. Unfortunately, none of these export regulations have kept up with laser technology or the current isotope enrichment methods.

The Nuclear Regulatory Commission Title 10, Part 110 describes components under their licensing authority. They control features and materials that could be used for enrichment. There are safeguards and controls in place for centrifuge and gaseous diffusion, but not for AVLIS systems. The NRC forbids the export of "specially designed or prepared thin, porous filters, with a pore size of 10–100 nm, a thickness of 5 mm or less, and for tubular forms, a diameter of 25 mm or less, made of metallic, polymer or ceramic materials resistant to corrosion by UF6." [21] It also forbids the export of unique materials used in centrifuges. The materials needed for the high-speed centrifuges have incredibly high tolerances. They are defined in Part 110 as "Maraging steel capable of an ultimate tensile strength of 1.95 GPa or more," "aluminum alloys capable of an ultimate tensile strength of 0.46 GPa or more," or "filamentary materials suitable for use in composite structures and having a specific modulus of 3.18 × 106 m or greater and a specific ultimate tensile strength of 7.62 × 104 m or greater." [22] Containing these high specification materials is a vital safeguard against enrichment by traditional methods. Unfortunately, due to the explosion of laser technology, AVLIS equipment has yet to be adequately export-controlled.

Proliferation Concerns

The most significant concern for the AVLIS systems is proliferation on a magnitude previously unseen. It is tough to hide enrichment plants due to their size and power consumption, but the AVLIS method consumes less power and has a smaller footprint that is much easier to conceal. The lasers are not regulated to the same degree as centrifuge or diffusion components. With modern laser technology exploding, a laser once only used in labs can now be built in a basement. The concern is that a photonics research center at a university could be converted or double as a weapons enrichment facility, which has already occurred on a small scale.

It is possible to purchase all required components for an AVLIS system online. Additionally, it was discovered that the lasers one would use for AVLIS could be bought online without any oversite. [5] While all of the components have the capability of being purchased, it does not mean that their acquisition in bulk or sequence will not have effects or trigger an investigation.

Recommendations

AVLIS is inherently a simple and efficient process that makes uranium enrichment relatively easy, compared to other methods. The opportunities for nefarious clandestine use are genuine. There is no good way to truly ensure that no organization is building or has a working AVLIS. However, tracking experts or attempting to control the aftermarket sales of high-powered lasers and electron beams will help to reduce the chance of proliferation. If further safeguards are not put in place, AVLIS is a real proliferation threat.

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A Review of Breeder Reactors

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Introduction

Breeder reactors have long been a topic of interest to the nuclear science community. This is because they make more fuel than they consume, which would be of great benefit to the energy industry. They also are a source of plutonium which causes them to be a proliferation risk. As with most issues pertaining to nuclear topics, the breeder reactor is viewed on varying degrees along the scale of peaceful to militant use. The United States gave up its breeder reactor program in the 1990s due to the risk of global nuclear weapon proliferation it presented while other countries continue to pursue breeder reactor technology. This paper will explore the topic of breeder reactors. Considering the proliferation risks associated with breeder reactors, those involved in nuclear counterproliferation should be knowledgeable on breeder reactor technology and be aware of where breeder reactors are being used.

Reactor Theory

Before delving into breeder reactors, it is important to understand some basic nuclear reactor theory as it pertains to these devices.

The principal source of the energy for the nuclear reactor occurs through a reaction in the nucleus of heavy atoms called nuclear fission. Fission occurs when certain nuclei absorb a neutron and split apart. Nuclear fission can be viewed as a two-step process.[1] The first step is when a fissionable nucleus absorbs a neutron to become a compound nucleus. If the nucleus can be induced to fission with a low energy neutron, that nucleus is considered to be fissile.[2] Lamarsh considers the threshold between when a large nucleus can be called fissile is if fission can be induced through the absorption of a zero-energy neutron. The most commonly discussed fissile nuclei are uranium-235 and plutonium-239; however, other fissile nuclei are uranium-233 and plutonium-241. If a nucleus will fission after a neutron of sufficiently high energy is absorbed, the nucleus is considered to be fissionable.[3] The second step of the two-step fission process is that the compound nucleus then splits into two or more smaller fission fragments along with neutrons and kinetic energy within the resultant fission fragments and neutrons.[4]

There is a probability that neutrons impinging upon a particular nucleus will interact in a certain way. That probability of interaction is called the microscopic cross section, σ, and its unit of measure is in barns (b). One barn is equal to 10^{-24} cm^2. There are multiple ways that a neutron could interact with a given nucleus. Some of these interactions include elastically scattering (elastic scattering cross section, σ_e), getting absorbed and not resulting in fission but rather the emission of gamma radiation (radiative capture cross section, σ_γ), and getting absorbed and resulting in fission (fission cross section, σ_f). Each one has its own microscopic cross section. The sum of

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the microscopic cross sections for all possible interactions of neutrons with nuclei is known as the total cross section, σ_t. The total scattering cross section is the sum of the elastic and inelastic cross sections, $\sigma_s = \sigma_e + \sigma_i$. The sum of the cross sections of all absorption reactions is the absorption cross section, σ_a, which is the same as all microscopic cross sections that are not one of the two scattering cross sections , $\sigma_a=\sigma_t - \sigma_s$.[5] An important thing to note is that the microscopic cross section is energy dependent – the energy of the impinging neutron will affect the value of the cross section. This is a very important concept for nuclear engineering applications so it is worth repeating: cross section is a function of energy.[6]

Nuclear fission is the fundamental process upon which the nuclear reactor is designed. The fission of one fissile nucleus will produce neutrons and energy. Those neutrons will result in additional fissions of other fissile nuclei and so on. If the neutron population of the reactor system continues to grow, it is a self-sustaining nuclear reaction. The reaction's viability to sustain itself can be quantified through the multiplication factor, k. Lamarsh defines multiplication factor as [7]

$$k = \frac{(number\ of\ fissions\ in\ one\ generation)}{number\ of\ fissions\ in\ preceding\ generation}$$

The above expression explains how neutrons from one generation are compared against the neutrons from a preceding generation. The multiplication factor will indicate whether the assembly of fissile material has a neutron population that is attenuating, in a steady state, or growing. If the value of k is less than 1, then the fissile material assembly is considered to be subcritical. The value in the denominator of the above expression for k is greater than the numerator, and each successive generation of fissions is less than the previous generation. If the value of k is equal to 1, then the assembly of fissile material is considered to be critical, and the neutron population is at a steady state. Nuclear reactors seek to achieve a k value of 1. If the value of k is greater than 1, then the assembly of fissile material is considered to be supercritical. The value of the numerator is greater than the denominator in the expression for k above, and the neutron population is growing.[8]

The average amount of neutrons released per fission for a particular nuclide is represented by ν.[9] Recall that not all neutrons that are absorbed in the fuel, or captured, result in fission. Considering this, another important parameter in nuclear reactor analysis applications is the capture-to-fission ratio which is defined by [10]

$$\alpha \equiv \frac{\sigma_\gamma}{\sigma_f}$$

Duderstadt and Hamilton define η as the average number of neutrons produced per neutron absorbed in fuel.[11] For a reactor to be critical, the value of η must be greater than 1. For values less than 1, the reactor will gradually lose neutrons.[12] For nuclear reactor fuel consisting of a single isotope, the following relation holds true[13]

$$\eta = \frac{\nu\sigma_f}{\sigma_a}$$

When a neutron is born from a fission event, it has a high amount of energy. These high energy neutrons are referred to as fast neutrons and have energy on the order of 1-2 MeV. Neutrons that are of lower energy of approximately 0.0253 eV are referred to as thermal neutrons. Fission that occurs from a fissile nucleus absorbing a thermal neutron and undergoing fission is referred to as thermal fission. The average energy for prompt neutrons released from U-235 thermal fission is 1.98 MeV and the most probable energy is 0.73 MeV.[14] The fission cross section for fissile nuclides is smaller for high energy neutrons than for low energy neutrons. The neutrons are slowed down, or thermalized, through a series of scattering interactions between the neutrons in the reactor system and a moderation material. Commonly used moderators include water, heavy water (D_2O), and graphite (carbon). These moderators are also often used as the coolant for the reactor, and nuclear reactors that rely on the fissions from thermal neutrons (neutrons that have energy of approximately 0.0253 eV) are known as thermal reactors. Those reactors that rely on a fast neutron spectrum are known as fast neutrons. The coolant for one type of fast reactor, the liquid metal fast breeder reactor (LMFBR), is sodium. This coolant is used because it is not an effective moderator which keeps the neutron population primarily in the fast energy spectrum.[15]

In addition to fissile and fissionable nuclides, another type of nuclide that is of interest in the nuclear energy field is the fertile nuclide. When fertile nuclides undergo radiative absorption, it results in a series of nuclear decays that ultimately yield a fissile nuclide. Two of the most useful absorption and subsequent decay chains are the following.

$$^{238}U(n,\gamma)^{239}U \xrightarrow{\beta^-} {}^{239}Np \xrightarrow{\beta^-} {}^{239}Pu$$

$$^{232}Th(n,\gamma)^{233}U \xrightarrow{\beta^-} {}^{233}Pa \xrightarrow{\beta^-} {}^{233}U$$

These are useful absorption and subsequent decay chains because of the abundance in which U-238 and Th-232 deposits are found throughout the world.[16] The process of fertile nuclides absorbing a neutron and undergoing transmutation to a fissile nuclide is known as conversion. If more fissile material is produced from fertile material than is consumed in the reactor, then instead of being called conversion it is called breeding and the reactor is called a breeder reactor. For a reactor to breed fissile material, the value of η must be greater than 2. This is because one neutron must be used to maintain criticality while another will be required to continue breeding.[17] U-233 has the largest η at thermal energies and so the Th-232, U-233 cycle offers a better option for thermal breeding. The light-water breeder reactor (LWBR) and the molten salt breeder reactor make useful thermal breeder reactors using the thorium cycle. The U-238, Pu-239 cycle lends itself better to fast breeding under as little neutron moderation as possible, or under as "hard" a neutron spectrum as possible. A hard neutron spectrum refers to a faster (or higher energy) neutron spectrum and a soft neutron spectrum refers to a more thermal (or lower energy) neutron spectrum. The LMFBR which uses liquid sodium as the coolant was introduced earlier. While the sodium coolant does have a softening effect on the neutron energy spectrum, sodium moderates neutrons much less efficiently than water or graphite. So LMFBRs leverage a fast, rather than a thermal, neutron spectrum to run the nuclear fission chain reaction. A way that these reactors are qualified is through the conversion ratio which is defined as the rate of the creation of new fissile material divided by the rate of destruction of existing fissile material. Should the conversion ratio exceed unity (more fissile material is being created than being destroyed), the conversion ratio is considered to be a breeding ratio.[18] While the value of η increases with neutron energy, the neutrons are less likely to interact with fertile and fissile nuclides and the values of capture and fission cross sections decrease. To leverage neutrons leaking out of the reactor core, the core of breeder reactors is surrounded by a blanket. The blanket is composed of fertile material, either thorium-232 or uranium-238 depending upon the particular reactor design, and it is designed specifically to capture neutrons and create more fissile material. Breeding of new fissile material can also be accompanied by a significant amount of fission so the blanket must be cooled along with the reactor core.[19]

A highly intensive process known as fuel reprocessing is required to extract the converted fissile material from the material that is not wanted in spent nuclear fuel such as the highly radioactive fission products.[20] Whether a particular fuel cycle employs fuel reprocessing and recycles fuel will determine whether that fuel cycle is an open or a closed fuel cycle. If the spent fuel is used only once and then ultimately put into dry storage, that is known as an open fuel cycle. This fuel cycle can also be referred to as the once-through fuel cycle or the throw-away fuel cycle.[21] If the spent fuel is recycled (there is still a lot of fissile material that remains in spent nuclear fuel), then that fuel cycle is considered to be a closed fuel cycle. To extract the fissile material that is converted in a breeder reactor, fuel reprocessing is required. Generally, countries that leverage breeder reactor technology employ a closed fuel cycle. See Figure 1 for a diagram of both the open and closed nuclear fuel cycle from the US Nuclear Regulatory Commission (NRC). The breeder reactor would fit into the "reactor" portion of this process flow.

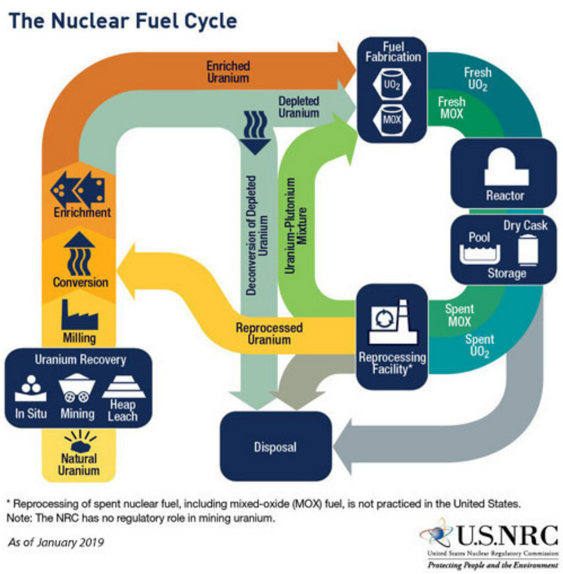

Figure 1. The Nuclear Fuel Cycle.[22]

History of Breeder Reactors in the United States

On the morning of 26 April 1944, Enrico Fermi, Leo Szilard, Eugene Wigner, Alvin Weinberg, and others met to discuss ways in which nuclear fission might be applied to provide power to cities. One issue at the top of everyone's mind was the scarcity of uranium at the time. So, the concept of the breeder reactor – where more fissile material is produced than is consumed – was very attractive. Fermi recruited Walter Zinn to the project, and Zinn became the first director of the newly named and reorganized Argonne National Laboratory (ANL) in 1946. On 19 November 1947, the Atomic Energy Commission (AEC) authorized ANL to build a liquid metal cooled fast neutron reactor which was named the Experimental Breeder Reactor-1 (EBR-I). The design team for EBR-I chose to cool the reactor core with a sodium potassium (NaK) alloy which would burn in air. Due to public safety concerns of building the reactor near Chicago, a remote site was chosen near Arco, Idaho. The site had formerly been the site for testing naval ordnance, and it became known as the National Reactor Testing Station. This site later became its own national laboratory apart from ANL, and later named Idaho National Laboratory (INL). EBR-1 was designed to both breed plutonium and generate electric power. On 20 December 1951, EBR-1 went critical and lit four 200-watt light bulbs becoming the world's first nuclear power plant to generate electricity. EBR-I operated until 30 December 1963 after which it was shut down.[23]

Experimental Breeder Reactor-II (EBR-II) was also built at the National Reactor Testing Station (later a site within INL) and criticality at low power without sodium coolant was achieved on 30 September 1961. It then achieved criticality with sodium coolant on 11 November 1963, and it achieved design power on 25 September 1969. EBR-II successfully demonstrated a sodium cooled fast breeder reactor functioning as an electric power producing nuclear reactor. One feature of EBR-II that helped make it successful was the adjoining Fuel Cycle Facility (FCF – now known as the Fuel Conditioning Facility at INL) that allowed for the onsite reprocessing and recycling of the spent highly enriched uranium (HEU) fuel that was used in EBR-II. The FCF reprocessed spent fuel from EBR-II and fabricated fresh fuel from 1964 until 1969. In 1967, EBR-II shifted from a demonstration power plant to an irradiation facility instead. EBR-II along with the FCF served as research and development facilities for the Integral Fast Reactor (IFR) concept out of ANL. The IFR program was terminated in 1994 and EBR-II subsequently shut down its operations in September of 1994 after 30 years of operation.[24]

The IFR was an ANL effort that rose in the wake of the failed Clinch River Demonstration Breeder Reactor (CRBR). The CRBR was intended to be an LMFBR demonstration plant, and the CRBR began with statutory authorization to several commercial power companies that included the Tennessee Valley Authority (TVA) and Commonwealth Edison Co. (now Exelon) along with the AEC. Westinghouse Electric Corporation was ultimately selected to manufacture this proposed demonstration LMFBR. Construction of the CRBR was projected to begin around 1974 or 1975 with power generation to begin around 1981 or 1982. The site of the CRBR was selected to be located on the Clinch River on the Oak Ridge, Tennessee, AEC site. TVA would operate the plant, and it would supply power to the TVA grid. The reactor was to be a loop-style sodium cooled fast breeder reactor that ran off plutonium mixed oxide (MOX) fuel. However, beginning in 1972, the LMFBR and CRBR programs began to generate particularly fierce public opposition.[25]

Building on a 28 October 1976 decision by President Ford, on 24 March 1977, President Carter directed the indefinite deferral of commercial reprocessing and plutonium recycling of spent nuclear fuel within the United States. President Carter also suspended the licensing process that was needed to gain a Limited Work Authorization for the CRBR in the same 24 March 1977 directive. The decisions by Presidents Ford and Carter were in large part a response to India's use of separated plutonium that it acquired through the assistance of the United States as part of the "Atoms for Peace" program. India had used this plutonium to execute a successful nuclear weapons test in 1974. At that time, there was growing concern resulting from Brazil, Pakistan, and South Korea all having made contracts with France and Germany for purchasing reprocessing plants. The United States suspected that all three of these countries were interested in pursuing a nuclear weapons program with the separated plutonium these reprocessing plants would provide them with.[26]

Despite opposition from the Carter Administration, Congress continued to fund the CRBR even though site construction could not proceed. The project merely ordered parts and stored them in a warehouse in the hopes that the political climate would change. In 1981, President Reagan restarted the CRBR construction licensing process. By the end of 1982, the design was mostly complete with most components either ordered or on hand. However, on 23 October 1983, Congress terminated funding for the CRBR for FY1984. On 15 December 1983, the Nuclear Regulatory Commission terminated the licensing process for the CRBR and vacated the Limited Work Authorization that it had granted the previous year. These actions essentially ended breeder reactor development in the United States.[27]

The IFR was put forth as a project following the failure of the CRBR project and the corresponding regulatory environment at the time that prohibited commercial spent fuel reprocessing. The IFR was touted as a critical step in making the breeder reactor concept economical, proliferation-resistant, and acceptable from an environmental standpoint. The IFR would leverage pyroprocessing and electrorefining as the method of extracting plutonium from the spent fuel. The IFR received federal funding for approximately a decade until ultimately it too was cancelled under the Clinton Administration. Funding for the IFR was terminated in 1994. As a political compromise however, the FCF was allowed to continue operations with research there being renamed the "actinide recycling project" and being applied to the long-term management of nuclear waste.[28] See Figure 2 for a timeline of the previously mentioned events.

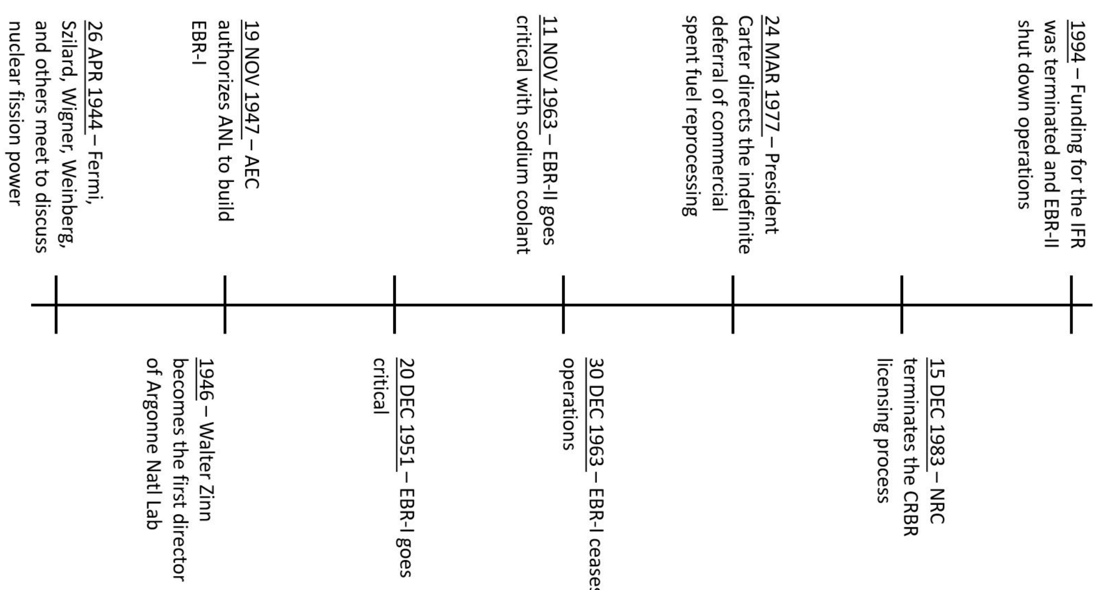

Figure 2. Timeline of the LMFBR History in the United States. (Image created by the author.)

There are many reasons why something as promising as breeder reactors ultimately failed in the United States and in Europe. Frank von Hippel, in an International Panel on Fissile Materials (IPFM) publication, argues that the reasons behind developing and implementing breeder reactors in the early days of nuclear power research and development can be attributed to the following four assumptions.[29]

1. Uranium is a scarce resource and uranium deposits would quickly be used up if the nuclear fission reactors achieved wide-spread use.
2. Breeder reactors would quickly be able to compete with the light water reactors that are currently used.
3. Breeder reactors could be as safe and reliable as light water reactors.
4. The proliferation risks posed by the recycling of fissile materials, particularly plutonium, that results in a closed fuel cycle could be managed.

Frank von Hippel is among those who feel that each of these assumptions proved to be incorrect.

Uranium ultimately became more prevalent and economically viable resource than originally thought. During the years preceding World War II and the Manhattan Project, uranium deposits were mined largely for their radium content. Aside from a few uses such as serving as color for ceramics and in steel alloys, most of the uranium that was mined for its radium content was discarded as waste. After its use for fission was discovered and demonstrated, it was initially thought that uranium deposits were a rare occurrence throughout the world. The United States briefly sought to monopolize these deposits as a way of controlling nuclear weapon proliferation in the hopes of limiting the special nuclear material that other countries had access to. In addition to continuing to discover useful uranium deposits, it was discovered that uranium could be extracted from a large variety of different ore types. Even ocean water contains about 0.002 ppm uranium.[30] Useful uranium ore deposits were discovered in countries around the world.

Contrary to breeder reactors rapidly being able to compete economically with light water reactors, breeders are still an enormously expensive undertaking and have not been able to compete with light water reactors yet. Unless the cost of uranium were to become significantly higher than it currently is, breeder reactors will have trouble competing with light water reactors. It could be argued that one contributing cost to the great expense of breeder reactors is that they were never built at large scale production capacity but rather a demonstration breeder reactor here and a demonstration breeder reactor there. Frank von Hippel asserts that there are few that would argue that even with breeder reactors being built at capacity, their capital costs would be able to drop below 25% greater than what it costs to produce power from comparable water-cooled reactors.[31]

Fast neutron reactors typically use sodium as the coolant. There are admittedly some safety benefits to using sodium over water as the coolant. For example, loss of coolant is a major safety concern for water cooled reactors. A break in the primary loop, or the coolant loop that is immediately in contact with the reactor core, can result in a loss of pressure and the water flashing to steam. For sodium cooled fast reactors, unless the break occurs below the reactor vessel, the sodium is kept at low pressure so the sodium will continue to cover the core and provide coolant to the core. If the break occurs below the reactor vessel, the liquid sodium coolant will flow out where the break is and leave the reactor core exposed. While there are safety benefits to the LMFBR design, there also are some severe safety concerns with using sodium as a coolant. One issue is that sodium is highly reactive with water and burns if exposed to air. Russia's BN-350 and BN-600 reactors and Japan's Monju reactor have all experienced sodium fires which caused significant delays and shutdowns. The sodium used in the fast reactors is also very radioactive. Sodium-23 is the stable isotope of sodium that is used in the coolant loops. When subjected to the high neutron radiation environment that surrounds an active reactor core, sodium-23 can absorb a neutron to become sodium-24 which has a 15-hour half-life. The primary sodium coolant loop becomes extremely radioactive. When considering the hazardous situation that would be created by a combination of this radioactive sodium with water, a radioactive sodium fire would be very dangerous. To mitigate this potentially catastrophic scenario, an intermediate sodium loop is inserted between the primary sodium loop cooling the fast reactor core and the steam generators so that it is the non-radioactive sodium that passes by the steam and not the radioactive sodium from the primary coolant loop. Adding this additional intermediate sodium loop with associated pumps adds to an already expensive facility.[32]

Sodium cooled fast reactors also have some serious reliability concerns. The fact that sodium cannot come in contact with the water in the air makes repairs very complicated. The liquid sodium is highly corrosive, and if there is a maintenance issue within the reactor, the reactor must be shut down, the fuel must be removed, the sodium must be drained, and the system must be flushed to ensure there is no residual sodium left that could cause an explosion or a sodium fire. This whole process could take months or even years. This results in long periods where the reactor is not producing power, further degrading its economic viability.[33]

By the nature of the breeder reactor fuel cycle, fissile material – especially plutonium – must be extracted from the spent nuclear fuel and the reactor blanket through reprocessing techniques. This provides access to plutonium that could then be diverted for use in weapons. There are concrete examples of the diversion of plutonium from use towards energy to use towards a weapons program. In 1974, India used some of the first plutonium that it extracted as part of its breeder reactor program to conduct what it called a "peaceful nuclear explosion". Typically, the plutonium inside spent nuclear fuel is considered to be self-protecting because the fission products make it so radioactive that handling it becomes extraordinarily difficult boarding on the untenable. As part of any breeder reactor program, the fissile material (and for fast breeder reactors that fissile material is plutonium-239) is extracted from those highly radioactive fission products that make the spent nuclear fuel self-protecting. Doing this inherently results in proliferation risk.34

Current Breeder Reactor Programs

While breeder reactor technology did not take off in Western countries, the concept is very much alive in India, Russia, and China. In India, the fast breeder test reactor (FBTR) is currently operational. India plans to use a three-stage process where it first would breed plutonium from uranium-238. That plutonium would then be used for stage II where it would be burned in fast breeder reactors where thorium-232 would be used in the blanket to make the fissile material of uranium-233. Stage III would consist of burning the uranium-233 to generate power and to convert more thorium-232 into uranium-233. It is currently working on its first prototype fast breeder reactor (PFBR) as part of Stage I.[35]

Russia currently has two fast reactors operating in Beloyarsk units 3 and 4 – the BN-600 (600MWe) and the BN-800 (880 MWe) which are both sodium cooled. It currently is working on the completion of the BN-1200 fast reactor which is planned for unit 5 at the Beloyarsk nuclear power plant. There are also plans in Russia to commission a 300MWe lead cooled BREST-OD-300 fast neutron reactor to be built in Seversk as part of the Siberian Chemical Complex.[36]

China currently has an operational pilot 20 MWe fast reactor – the China Experimental Fast Reactor (CEFR). The CEFR went critical in 2010.[37] As of earlier this year, China has started work on building a second spent fuel reprocessing plant that is anticipated to be complete by 2030. China is also building fast breeder reactors. Among others, this work on reprocessing facilities and fast breeder reactors has concerned the US defense establishment. In April of 2021, Admiral Charles Richard, the commander of US Strategic Command, told the Senate Armed Services Committee that "with a fast breeder reactor, you now have a very large source of weapons grade plutonium available to you, that will change the upper bounds of what China could choose to do if they wanted to, in terms of further expansion of their nuclear capabilities."[38] The China National Nuclear Corporation is building two China Fast Reactors (CFR-600) on the island of Changbiao in Fujian province. These reactors are sodium cooled fast reactors designed to produce 600 MWe. The first of these two reactors is scheduled to start producing power in 2023 and the second is scheduled to start producing power in 2026.[39]

As the United States seeks ways to lower its carbon emissions, there is currently significant interest in advanced nuclear reactor designs within the United States from companies such as Westinghouse, GE Hitachi, and X-energy. The US based company TerraPower is explicitly pursuing breeder reactor technology. It is currently working on several reactor designs that include the Natrium Reactor Design, the Traveling Wave Reactor Design, and the Molten Chloride Fast Reactor Design.[40]

While there is interest in breeder reactor designs, there are currently no operational breeder reactors in the United States. France, Japan, the United Kingdom, and the United States have all seriously pursued breeder reactor development and construction with operational breeder reactors at various points.[41] Not all of these breeder reactor efforts were tied to weapons programs, but rather, many were designed for peaceful energy purposes. Currently however, only India, Russia, and China are operating breeder reactors. In the Bulletin of the Atomic Scientists article "It's Time to Give Up on Breeder Reactors" by Cochran et al., the authors make the observation that "[t]he persistence of breeder programs in Russia, India, and China is testimony to the ability of their nuclear establishments to tap into national treasuries despite the fact that breeders will not be able to compete with light water reactors for the foreseeable future."[42]

Breeder reactors are designed to produce fissile material, and that fissile material has the potential to be diverted to a weapons program. JP 3-40, Joint Countering Weapons of Mass Destruction, provides the organizing principles of prevent, protect, and respond. To counter a country's efforts to develop nuclear weapons of mass destruction, paying attention to the country's breeder reactors can provide a focal point for information on weapon production pathways. Under the prevent organizing principle, there is the specialized activity of WMD pathway defeat and the specialized tasks of dissuade, deter, delay, disrupt, destroy, deny, and assure. By having relevant agencies, units, and organizations perform these specialized tasks against a key node in the nuclear fuel cycle, this can aid in preventing the country from acquiring nuclear weapons.[43]

Under the protect organizing principle, there is the specialized activity of WMD defeat and the specialized tasks of control, defeat, disable, and dispose. If a country has been found to have been diverting fissile material from a breeder reactor to a weapons program, the organizing principle of protect becomes more relevant regarding the breeder reactors. If there is a way of removing the breeder reactor from the country's nuclear weapons production network, that would eliminate the supply of fissile material and it would hinder the ability to produce nuclear weapons.[44]

Under the respond organizing principle, there is the specialized activity of CBRN response and the specialized tasks of attribute, mitigate, sustain, and support. Regarding this organizing principle, understanding the country of concern's breeder reactors would assist in determining the nature of the plutonium in the weapons that are being produced.[45]

In addition to the organizing principles of prevent, protect, and respond, there are the crosscutting activity and tasks of understand the environment, threats, and vulnerabilities and locate, identify, characterize, assess, and predict. This activity and these tasks are applicable throughout the countering weapons of mass destruction (CWMD) spectrum of activities. It is important for those agencies and organizations that are involved in the CWMD community to be aware of breeder reactor programs within strategic competitors and countries of concern. Analysis of these facilities can provide warnings and indicators of emerging and existing nuclear weapon programs.[46]

Breeder reactors are appealing from the perspective of closing the nuclear fuel cycle and creating more fissile material than they consume. They are also a proliferation concern as they extract fissile material from spent nuclear fuel. Even though there are no operational breeder reactors in the United States, it is important for those involved in nuclear counterproliferation to understand breeder reactors and be aware of where they are being used in the World.

For additional information on breeder reactors, here are a few suggested online resources.

For additional information on how breeders work:
Breeder Reactors by Walter Mitchell, III and Stanley Turner from the US AEC's Understanding the Atom Series (1971).

<https://www.osti.gov/includes/opennet/includes/Understanding%20the%20Atom/Breeder%20Reactors.pdf> accessed on 25 November 2021.

For additional information on the history and status of different countries' breeder programs as of February 2010:
Fast Breeder Reactor Programs: History and Status by Thomas Cochran et al. from the February 2010 report by the International Panel on Fissile Materials.
<https://fissilematerials.org/library/rr08.pdf> accessed on 25 November 2021.

For a good comprehensive history of fast breeder reactor development in the United States:
"Fast Reactor Development in the United States" by Thomas Cochran et al. published in Science & Global Security (2009).
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Designing a Graphite Moderated Sub-Critical Assembly for the United States Military Academy Nuclear Engineering Program

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United States Military Academy Class of 2021 Nuclear Engineering Program

[Editor note: This is the work of a USMA Nuclear Engineering Capstone Design Project during the 2020-2021 academic year. USMA will repurpose graphite blocks from AFFRI in order to have a graphite moderated subcritical assembly in addition to a water moderated subcritical assembly. A second capstone design group is working in 2021-2022 academic year to construct the assembly and an updated article is expected next year.]

Introduction

Problem Statement

The Department of Physics and Nuclear Engineering (PANE) at The United States Military Academy (USMA) requested the design and construction of a Graphite Moderated Sub-Critical Assembly. This assembly will be utilized by future Nuclear Engineering students for experimental learning and research.

Previous Work

The Pennsylvania State University Subcritical Graphite Reactor Facility serves as a great base of research for the USMA design. The assembly has been used for research since its construction as a graduate student project in 1958. The assembly measures 266 cm x 161.5 cm x 178 cm and utilizes up to five neutron sources of PuBe or ^{252}Cf. The graphite assembly features removable uranium rods that are loaded horizontally and have a removable cadmium cover. Depending on the geometry of the fuel, the assembly can be used for diffusion length, thermal neutron field, or approach to criticality experiments.[1]

The Massachusetts Institute of Technology (MIT) Graphite Exponential Pile measures 231 cm x 231 cm x 297 cm and utilizes uranium slugs as fuel. Like the assembly at Pennsylvania State University, the rods are horizontally loaded and can be configured in multiple geometries to manipulate the neutron flux. The assembly typically utilizes a 12 x 12 geometry of fuel slugs and has a vertical line

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of smaller diameter holes through the center of the assembly for detector insertion. Furthermore, the assembly has a pedestal of graphite on the bottom, in an area where fuel cannot be loaded. MIT uses this graphite pedestal to thermalize neutrons before they enter the assembly and increase its criticality.[2]

Theory

The moderating properties of graphite have been well studied since its first use as a moderator in the Chicago Pile-1. For a material to moderate neutrons, it must have a low atomic number (Z) as neutrons are moderated through scattering. Given that graphite is composed of mostly carbon with an atomic number of six, incident neutrons can lose a significant amount of energy after a single collision. Another material property of graphite that makes it a good moderator are its microscopic cross sections. Measured in barns, the microscopic cross section translates to the probability that a neutron interacts with the nuclei of the target atom. Ideal moderators have very high microscopic scattering cross sections and very low microscopic absorption cross sections. Under these conditions, neutrons are much more likely to lose energy through a collision than be absorbed in the nuclei of the moderator. The use of moderator allows the slowing of the neutrons to thermal speeds and thus the probability of the neutron causing a fission in the fuel is significantly higher.

The diffusion length of graphite is also an important factor in the design of the assembly. Diffusion length refers to the average distance a neutron travels before it is absorbed. Graphite has a diffusion distance of approximately 59 cm; for comparison, light water (H2O) has a diffusion length of 2.85 cm[3]. This means that a significantly thick moderator blanket is required for ample neutron moderation in graphite This is a challenge as the available space and material will limit the thickness of moderator in the design. One application for the graphite-moderated subcritical assembly is for k-value calculations. The k-value describes neutron production as it is the ratio of neutrons in a generation to neutrons in the previous generation. A subcritical assembly requires a k-value below 1.0. The k-value may be modeled by utilizing Monte Carlo N-Particle Transport (MCNP6). MCNP6 is a program designed to model problems such as radiation shielding, reactor design, and other nuclear science applications.

The moderator plays a large role in the determination of many of these variables. The fuel utilization factor *f* is the ratio of thermal neutrons absorbed in the fuel to thermal neutrons absorbed in all materials. A good moderator such as graphite has a low thermal neutron absorption probability and therefore allows for a higher *f*.

Constraints, Limitations, and Specifications

The USMA assembly was specified to have multiple fuel loading configurations, a design which allows for k-value and diffusion length experiments and can fit reasonably in the department's nuclear experimentation room. The graphite blocks to be used measure 10 cm x 10 cm x 150 cm.

In order to meet the specifications, the graphite moderator must be removed in a way that allows for fuel rods to be inserted in multiple locations. The graphite moderator blocks must be cut to allow the 3.35 cm diameter fuel rods to be inserted, as seen in Fig 1. Additionally, the assembly must allow for detector insertion in multiple locations to conduct experiments. Lastly, the entire assembly dimensions must not exceed 2m x 2m x 2m in order to be used in the desired nuclear laboratory room.

The design is limited by the physical properties of the graphite moderator. Graphite is a solid, and therefore fuel rods cannot be inserted into the assembly simply by displacing the graphite moderator as with water moderated assembly. Additionally, graphite's diffusion length is much larger than other thermal reactor moderators such as water. This means that neutrons moderated by graphite must interact with more graphite atoms before they are thermalized and can be absorbed. This presents a challenge to the design due to increased fast neutron leakage.

Methods

Before constructing the assembly, modeling and simulation software confirmed the validity of the design. MCNP6, VISED, and SolidWorks were used to model the design. MCNP6 was utilized to model the graphite assembly and to conduct diffusion length and criticality calculations.

VISED is a visual editor powered by MCNP6 which produces a visual representation of the MCNP6 input. VISED was used primarily to confirm the geometry was valid. SolidWorks provides another visual representation of the assembly with materials specified. Mechanical drawings can also be created through SolidWorks to show specifications of the design.

Results

Unit Cell Design

Unit cells are the building blocks which will be used to build the assembly in MCNP6 or SolidWorks. In order to use materials efficiently and maximize the volume of graphite in the assembly, each unit cell in the assembly will have the same dimensions as an individual graphite block. The assembly will be comprised of two main unit cells. The first is a unit cell of graphite moderator, and the second is being a unit cell comprised of a fuel rod and graphite moderator. The unit cells are shown in Fig. 1.

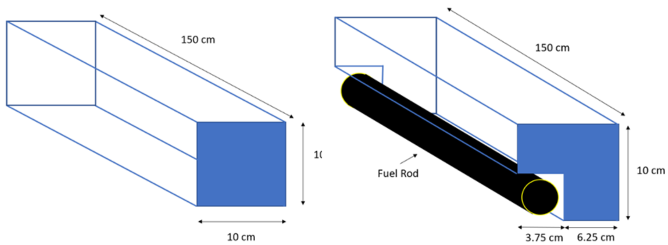


Figure 1. Unit cell of graphite moderator (left) and fuel rod in graphite moderator (right) (Author produced drawing)

Of note, on the right side of Fig. 1, a 3.75 cm x 3.75 cm x 150 cm rectangular prism of graphite is removed from the bottom left of the unit cell in order to place the fuel rod. This size was chosen to accommodate any imperfections in the fuel rods, as well as to facilitate easy loading and unloading of the fuel rods. Furthermore, the corner of the unit cell was chosen for the location of the cutout as it requires only two cuts to remove the graphite prism. This method of machining allows the removed graphite to be retained geometrically intact. Although there is a small amount of material lost due to the sawblade kerf, the removed graphite can be inserted to have a nearly solid graphite block. The cut block with material reinserted will be modeled as the unit cell on the left of Fig. 1.

Assembly Design

The assembly was created following completion of the unit cell designs. In order to maximize the size of the assembly within size constraints, the design need to use the 300 graphite blocks efficiently. This was achieved by stacking the graphite blocks in rows and columns with the long axis of the blocks oriented in a single direction. An arrangement of 15 rows of 20 horizontal blocks was chosen and is shown in Fig. 2.

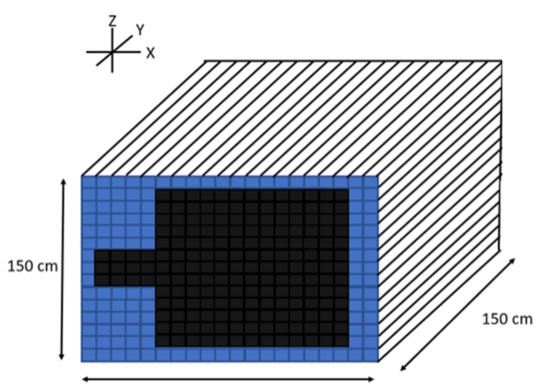


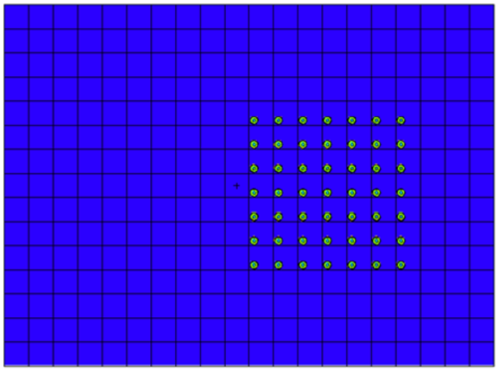
Figure 2. Arrangement of graphite blocks in the assembly. Blue cells are uncut graphite and black cells are cut graphite. (Author produced drawing)

This arrangement of the assembly places the overall dimensions at 2.0 m x 1.5 m x 1.5 m. Due to the number of graphite blocks available, this arrangement uses the highest whole number integer closest to a square. Furthermore, assuming the assembly will only be loaded in a square configuration, this arrangement also creates a pedestal of graphite similar to MIT's assembly which will aid in diffusion length experiments.

Given the chosen arrangement, the maximum fuel rod loading capacity would be a 13 x 13 square with a 10 cm pitch. However, 181 out of the 300 graphite blocks will be cut to the specifications in the right of Fig. 2. These cuts may serve as both fuel rod locations and detector insertion points. Therefore, there exists multiple configurations of the fuel rods with pitches starting at 10 cm and increasing by increments of 10. Due to graphite's moderation properties, any increase in criticality from the number of loaded unit cells may be offset by an increase in leakage due to a lower number of neutrons being thermalized as a result of the missing moderator in the corresponding location. This is because roughly 14% of the moderator's volume is removed for every loaded unit cell.

MCNP Analysis

MCNP6 was the main method of evaluation for the design. It provides accurate modeling of neutron transport and yields results practical for design determinations. The first loading configuration tested used 49 fuel rods in a 7 x 7 arrangement with a 10 cm pitch. A cross sectional view of this loading configuration is shown in left of Fig. 3.



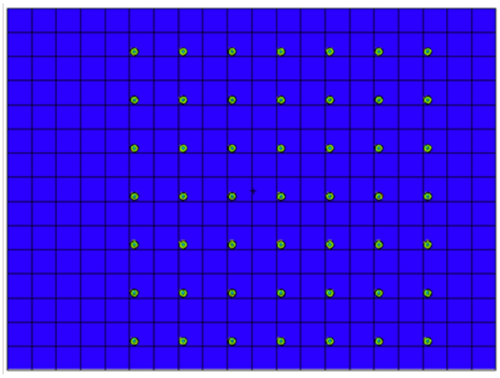


Fig. 3. Cross Section of 7 x 7 loading configuration with 10 cm pitch (left) and 20 cm pitch (right) modeled in MCNP. (Author produced drawing)

Due to graphite's large diffusion length, if the loading configuration was modeled at max capacity, the K_{eff} would be roughly similar while drastically losing efficiency. At max loading, 169 fuel rods would be used. This increase in the number of fuel rods would minimally raise the K_{eff} as the amount of graphite lost due to the fuel rods being inserted would lower the K_{eff}.
Therefore, it was decided to maintain 49 fuel rods as a base number and increase the pitch to 20 cm and observe its effects. A cross sectional view of this loading configuration is shown in right of Fig. 3. A summary of the results is shown in Table I.

Pitch (cm)	K_{eff}	Absolute Uncertainty	Standard Deviation
10 cm	0.623	0.003	0.00134
20cm	0.645	0.002	0.00122

Table 1. MCNP modeled Keff comparison of pitch configuration (Author produced table)

Final Design

Upon receipt of the graphite blocks, 181 will be cut in accordance with Fig. 1. They will be machined using a table saw with a carbide-tipped blade to avoid cracking in the graphite. Figure 4 shows the results of a practice cut on scrap graphite.

Fig 4. Experimental cut of graphite unit cell (Author picture)

The machined graphite blocks can be manual configured as either of the two unit cellspr. Fig. 5 depicts unloaded and loaded unit cells near full insertion of a graphite moderating rod (left) and an aluminum cladding tube in which the uranium fuel will be contained (right).

Fig. 5. Examples of unloaded (left) and loaded (right) unit cells (Author picture)

Additionally, the assembly can be described as 20 columns of 15 blocks stacked on each other, as there is no internal structure to house the assembly. To ensure the assembly is structurally stable and safe to operate around, a frame was constructed using slotted aluminum. The frame, loaded with some test graphite blocks, is shown in Fig. 6

Fig. 6. Aluminum frame to house graphite assembly (Author picture)

In addition to the aluminum shell, borated polyethylene sheets measuring no less than 1 cm thick will be secured to all sides of the shell to provide neutron shielding for operators. An MNCP6 input was created to model the shielding for the assembly. The shielding consisted of a 1 cm shield of borated polyethylene. The shield was able to reduce the neutron flux by a factor of 3 at the edge of the assembly. Additional calculations are needed to determine the exact amount of shielding needed on each side of the assembly.

Finally, standard operating procedures (SOPs) for diffusion length and approach to criticality experiments will be developed for future students to follow in laboratory experiments. These SOPs will include operating instructions, proper methods for data collection, protective equipment needed, general safety, and inspection checklist to ensure proper maintenance of the assembly.

This design will be passed on to a follow-on group who will continue with this multi-year capstone design. The groundwork is laid with MCNP6 and SolidWorks files. Proof of concept machining tests have been performed. Initial shielding calculations are complete. The group that takes on this project will focus on the logistics of getting the graphite blocks on site and then actual construction of the assembly.

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United States Military Academy Cadet in the Department of Chemistry and Life Science working in laboratory iwhich is a requirement for many of the courses within the department.

Army Officer Corps Science, Technology, Engineering and Mathematics (STEM) Foundation Gaps Place Countering Weapons of Mass Destruction (CWMD) Operations at Risk – Part 1*

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**Note – This is the first of three articles from the authors describing the risk to Joint Operations incurred by an Army that is vulnerable to the STEM challenges faced in a great power competition involving CWMD operations. In this article, we describe the problem. In articles two and three of the series, we will elaborate on the problem utilizing the Joint Publication 3-0 as our guide and recommend solutions to address this gap.*

Situation:

Step inside nearly any university research lab and you will find few students destined to become Army officers. In January 2021, the Pentagon published the annual report on U.S. Defense Industrial Base Industrial Capabilities.[1,2] The findings are alarming: the lack of STEM educated Americans may lead to a "permanent national security deficit".[3] Both Russia and China are producing several times more STEM graduates than the U.S.[4] As a result of lacking enrollment by American students, the technical programs of U.S. universities are seeking foreign students to fill the gap.[5] More than half of foreign students in the U.S. universities are enrolled in STEM degree programs.

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During 2010-2019, approximately 42% of graduating STEM program Ph.D. students in the U.S. were from foreign nations.[6,7] In 2020, the majority of these students arrived from India (18%) and China (35%).[8,9] Consequently, the U.S. DoD and defense contractors suffer from a shrinking population of U.S. citizens with technical degrees capable of passing background investigations to obtain the necessary security clearances to support our Nation's technical defense requirements.[10]

Although the report focuses on education deficit in artificial intelligence (AI) and machine learning, similar trends remain true across the spectrum on STEM fields such as bioengineering, materials science, and chemical engineering, all critical to developing and transitioning key technologies for the Warfighter, as well as providing necessary expertise for the defense industry and higher echelon military staffs. Less than 20% of electrical engineering and computer science students are Americans.[11] This has a direct impact on national security given our increased reliance on artificial intelligence and cyber systems.[12] Perhaps in response to this STEM education deficit as articulated in the Pentagon Report, President Biden signed an Executive Order adding the Office of Science and Technology Policy (OSTP) as a cabinet-level agency.[13]

Not only are Chinese students dominating STEM fields in U.S. universities, China's national power is further demonstrated by superior performance among graduate doctoral programs. In August 2021, the Center of Security and Emerging Technology (CSET) presented data which demonstrated that China is fast outpacing U.S. STEM PhD Growth.[14] Since 2003, more Chinese graduate students earned PhDs in STEM fields than U.S. domestic graduate students.[15] Many of the Chinese PhDs are attained at top-tier U.S. institutions. By 2025, China is forecasted to produce more than three times as many STEM PhD graduates as the U.S.[16] The result is not by chance. China has spent significant resources developing its universities to strengthen Chinese human capital as part of "comprehensive national power".[17] China's success is not simply due to increased funding rather its focus and national resolve on increasing its STEM capacity.[18,19]

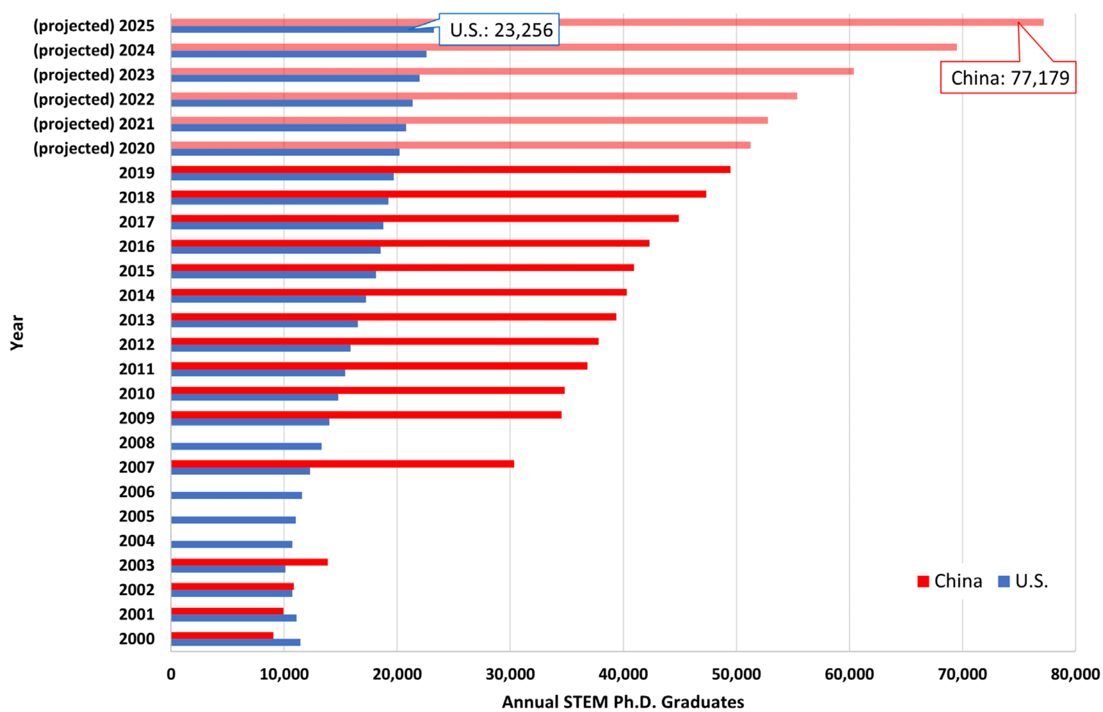

Figure 1. Data obtained from Georgetown University Center for Security and Emerging Technology.[20]

For perspective, though, a lack of STEM dominance among American students is not a new problem. After the U.S.S.R. successfully launched Sputnik into orbit in 1957, the U.S. government took aggressive action to improve science and math education.[21] In 1958, the National Defense Education Act authorized $1 billion to "overhaul the American education system from schools to universities at the federal level".[22] Soon, talented students benefitted from advanced placement in science and math courses where calculus became part of their high school curriculum. These specialized tracks enabled a large increase in STEM degrees beginning in the 1960s.[23]

The U.S. federal government by policy and funding levels continues to put a high premium on Science and Technology (S&T) research and education (~$120 billion annually between FY 2010-2017), which is the largest federal government investment of any world nation.[24] This problem and national vulnerability is well-known and is concerning to our national leadership. Key United States of America National Strategy documents identify that STEM competence, competition, and dominance is a national security priority: National Security Strategy (2017),[25] National Defense Strategy (2018),[26] a 21st Century Science, Technology, and Innovation Strategy for America's National Security (2016),[27] National Strategy for Countering Weapons of Mass Destruction Terrorism (2018),[28] and the National Biodefense Strategy (2018).[29] Though described differently across these documents, S&T advancement and primacy is linked to our Nation's strength and defense. Despite this emphasis and unifying theme, the Army Officer Personnel Management System (OPMS) and Officer Education System, to include Professional Military Education (PME), do not prioritize or effectively support our National Strategy because STEM competency is not prioritized through commissioning sources, educational opportunities, or PME.

Thesis:

The Army Officer Corps is developing a widening gap in STEM-discipline undergraduate and graduate degree expertise placing the United States at risk for Countering Weapons of Mass Destruction operations. Accordingly, STEM proficiency at the undergraduate-level and graduate-level is a critical component for all Army branches (not only Functional Areas / Medical Service Corps) and requires resourcing, opportunity, and advancement commensurate to its priority in the National strategy.

Need:

Army Officer regulations, practices, and priorities rightly emphasize leadership and command. Officers lead the Army. Commanders at all levels from the company to the component / combatant command apply mission command to command and control units to achieve the assigned mission.[30] Command is referred to as more "art than science because it depends upon actions only human beings can perform" and "incorporates intangible elements of authority, responsibility, decision making, and leadership".[31] ADP 6-0 elevates the art of war above the science of war; however, in CWMD multi-domain operations incorporating the six warfighting functions into effective decision making within mission command requires not only tactical competence but STEM competence. In CWMD multi-domain operations, the science of command surpasses the art of command. As illustrated in ADP 6-0, Figure 1-2, Combat Power Model,[32] the Commander and her / his staff must possess the S&T competence to unify these disparate functions: as each function becomes more technically complex, STEM competence and the critical thinking / technological competence provided through advanced STEM degrees are necessary on the tactical and operational levels to facilitate right decision making.

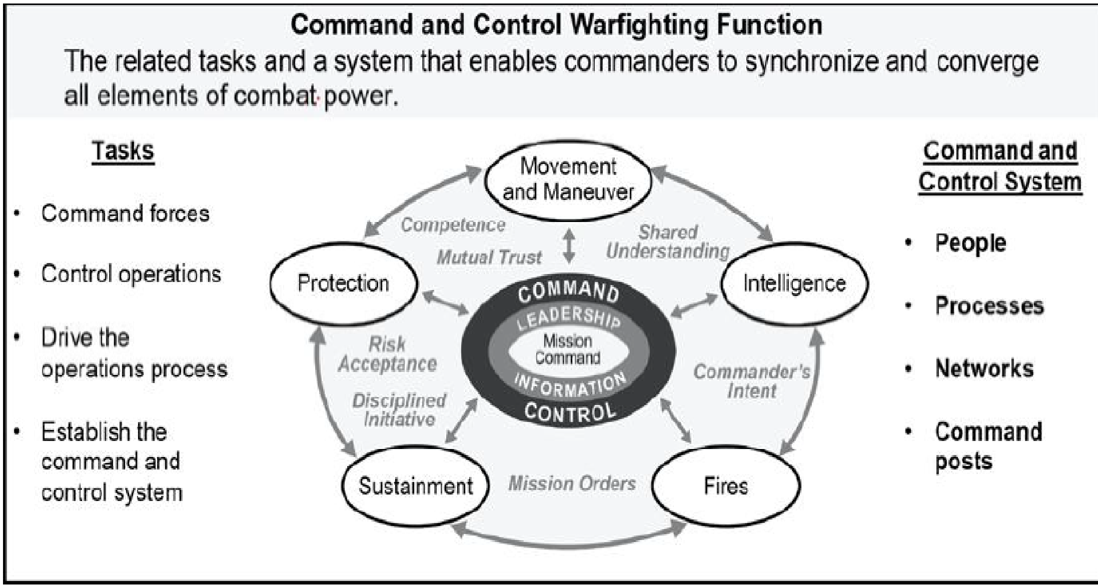

Figure 2. The combat power model illustrates the relationship between the six warfighting functions with command and control being the unifying function.[33]

A simple word search of key Army doctrine demonstrates the lack of emphasis on STEM / S&T competence in decision making and Army operations:

- ADP 3-0, Operations[34] (science always in relation to warfare, operations, or understanding)
- ADP 5-0, The Operations Process[35] (science always in relation to operations or understanding)
- ADP 6-0, Mission Command[36] (science always in relation to command, warfare, or information)
- ADP 6-22, Army leadership and the Profession[37] (science, no link to STEM / S&T)
- 2019 Army Modernization Strategy[38] (S&T emphasized but not in relation to officer competence)
- Army Chief of Staff Papers #1 and #2, March 2021[39,40] (S&T emphasized but not for officer competence)
- The Army People Strategy, October 2019[41] (only in relation to talent management improvement, not actual STEM competence)
- ATP 3-90.40, Combined Arms Countering Weapons of Mass Destruction[42] (one mention of forensic science)

As far as the Officer Education System, the FY20 and FY21 U.S. Army Accessions Mission Letter[43] for Officer Commissioning sources establishes a goal of 25% of contracted cadets assess in an undergraduate STEM program with overproduction encouraged (this excludes AMEDD with specific STEM accessions requirements). Indeed, the Army exceeds this goal for commissioning: the number of Army ROTC graduates with STEM degrees averaged ~30% in FY19-21 and the number of United States Military Academy graduates with STEM degrees is historically stable at approximately 50%.[44] Within PME, for senior company grade and junior field grade officers, STEM advanced degrees opportunities become available through three routes: a United States Military Academy (USMA) Advanced Civilian Schooling (ACS) fellowship, the broadening opportunity program or through Functional Area designation and qualification. Outside of those categories (and exceptions), PME and graduate-level education is devoted to non-STEM fields. And in fact, officers who pursue advanced civilian education opportunities in STEM will likely experience a delay in promotion due to an insufficient number of field-grade (O-5) evaluations, or pausing their promotion year group, as a result of their time in graduate school compared to officers who remain in operational assignments. At the Senior Service College / Fellowship level, PME is again focused on competence in strategy, federal government / international relations, and leadership instead of STEM competency.

This dichotomy between declaring a need for leaders competent in STEM and prioritizing the fulfillment of that need can be seen through the Army's FY2021 Broadening Opportunity Program catalog.[45] The catalog, which lists the assignments the Army will fund for broadening opportunities, has 15 opportunities for broadening assignments with graduate degree outcomes. Of those 15 opportunities, only two have the directive to focus on STEM related topics, the Purdue Military Research Initiative (PMRI) and the Army Futures Command Artificial Intelligence Scholar Program, and while the PMRI attempts to focus on STEM related degrees, it is not a requirement of the program. The cost of these respective programs available to STEM focused leaders versus their non-STEM counterparts is additionally concerning. PMRI falls into the "low cost" category for the Army's Advanced Civil Schooling program, meaning the Army pays under $26,000 per year per graduate student. Compared to the remaining 13 non-STEM focused programs, three are high-cost category which can be as much as $55,000 per year per student with an additional three programs that are either medium-cost or high-cost category depending on student selection. In essence, the Army places between a $17,000 and $29,000 premium on non-STEM related graduate degrees.

Accordingly, Field-grade and General Officers serving in critical Command billets from Battalion through Component / Combatant Commands largely lack the STEM expertise to integrate the technological advances of the warfighting functions most effectively. Among active-duty Army general officers, 10% earned a graduate degree in a STEM field and 30% completed undergraduate STEM programs.[46] Though possibly surrounded by staffs for functional area competence, their own limited understanding of STEM creates vulnerability and risk either through over reliance on S&T experts or personal bias with respect to S&T issues. These commanders have commanded at the most challenging operational assignments resulting in positions of command with increasing authority; however, the Army has not prioritized continued STEM education in their career progression and leader development.

Despite STEM-education and excellence being a National-priority as described in Executive Strategic policy documents, the Army does not prioritize STEM education either in accessions (30-50% accessed) or in the PME system. The Army is currently not aligned with the National Strategy for STEM dominance in the face of future CWMD operations in a great power competition. The Army's failure to emphasize STEM competence in the Army Officer Corps outside of Functional Areas creates risk to mission accomplishment in CWMD multi-domain operations. The Army must prioritize STEM education in accessions and throughout PME to prepare commanders for effective S&T informed decision making within mission command in CWMD multi-domain operations.

Approach:

In the next two CWMD Journal issues, the authors will argue our thesis utilizing JP 3-0 as a frame of reference for CWMD Operations. JP 3-0, Joint Operations, describes a Joint Operational Model with notional phasing for predominant military activities.[47] Applying the Joint Operational Model to a regional or great power competition involving CWMD operations provides a construct to evaluate how Army Officer STEM competence support Joint Operational success in each phase. Our next article (Part 2) will address the risk of our current efforts as we operate in Phases 0 and 1 (Shape and Deter) CWMD operations in multiple theaters of operation. Our final article (Part 3) will examine the transition to decisive action / unified action with Phases 2 - 5 (Seize the Initiative through Enable Civil Authority). Through this project, we will explore and identify specific risks to Joint Operations incurred by an Army that is ill-prepared to meet the STEM challenges faced in a great power competition involving CWMD operations. The goal of this project is to support our thesis through demonstrated facts and scenarios in order to convince Senior Leaders that a new prioritization of officer education to achieve STEM competence from undergraduate commissioning through senior service college or equivalent is required for the Army to support Joint CWMD operations in multi-domain operations.

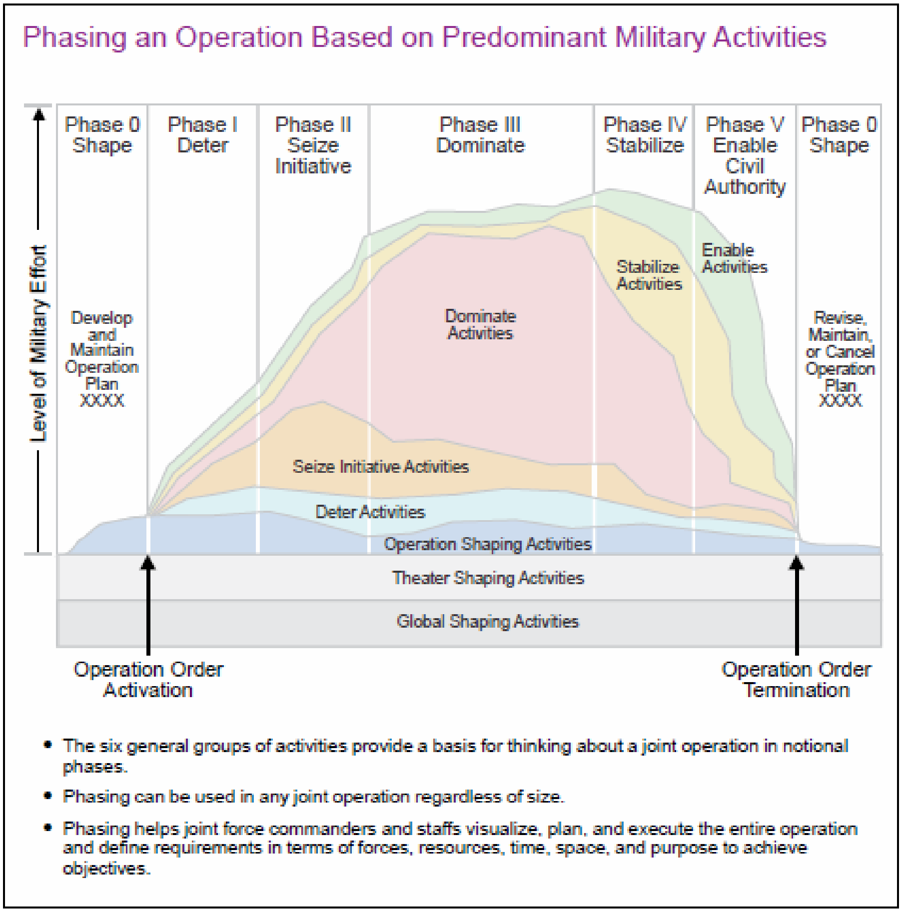

Figure 3. Applying the Joint Operational Model to a regional or great power competition involving CWMD operations provides a construct to evaluate how Army Officer STEM competence support Joint Operational success in each phase. Part 2 of our series will address Phase 0 and 1. Part 3 of our series will address Phases 2 – 5.[48]

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LTC Matt Gettings, during his Ph.D. research at Purdue University, holds a test container of silver salts, a new lead-free explosive that he synthesized in an Army funded research laboratory at Purdue.

Developing Future CWMD Leaders - DTRA Nuclear Science & Engineering Center Research Fellow and Summer Internships

MAJ Joshua D. Frey

DTRA Nuclear Science & Engineering Research Center

Introduction

The Defense Threat Reduction Agency is the DoD's Combat Support Agency responsible for enabling DoD, the U.S. Government, and International Partners to counter and deter Weapons of Mass Destruction (WMD) and Emerging Threats. [1] It does so through its core functions: enabling strategic deterrence, support to treaty monitoring and verification, partnering to reduce global WMD threats, identifying vulnerabilities and mitigation strategies, and developing and delivering rapid capabilities. DTRA's history is long and engrained in the development of nuclear weapons, nuclear diplomacy, and the realization of militarily useful technology to confront the challenges of chemical, biological, radiological, and nuclear weapons. One of its most important roles within the force development process is capability development for joint warfighter requirements to counter and deter WMD and emerging threats.

The Research and Development (R&D) Directorate provides the largest organizational component for technology maturation and risk reduction within DTRA, with the Nuclear Technologies Division (RDNT) being the primary developer for detection, survivability, weapon effects, assessment, integration systems, and software. RDNT uses multiple avenues to conduct technology maturation and risk reduction for materiel capability development. One of its primary mechanisms is through University Research Alliances (URA) to access the intellectual and research capital within civilian institutions. Additionally, RDNT established the Nuclear Science & Engineering Research Center (NSERC) in 2007 at West Point as the program manager for academic year research and summer internships within the DoD Degree Granting Institutions. Focused on engaging the faculty and students at the three service academies and two DoD graduate schools, the NSERC supports research focused on RDNT mission priorities and leverages the unique combination of student and faculty operational experience and defense-focused education and research programs to provide a novel research capability to the DTRA.

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Research Program Support to DoD Academia

The NSERC supports five research programs at the United States Military Academy (USMA), United States Naval Academy (USNA), United States Air Force Academy (USAFA), Air Force Institute of Technology (AFIT), and Naval Postgraduate School (NPS). This research spans the full breadth of the nuclear technology mission space, with projects aligned to RDNT mission areas: Detection, Effects, Survivability, Integration, and Assessments; and cross-cutting lines of effort: Conventional-Nuclear Integration/Battlefield Nuclear Warfare, Nuclear Planning Tools, Nuclear Wargaming and Analysis, Quantification of Nuclear Survivability and Effectiveness, Countering Nuclear Threats. The NSERC also supports other research projects in fundamental nuclear physics and emerging projects that require initial seed support to mature projects until they receive a long term sponsor, such as a National Laboratory collaboration.

NSERC Research Fellows

The NSERC Research Fellowship is a new program managed by the NSERC to provide direct support to officers performing academic research during Advanced Civil Schooling (ACS) in civilian academic programs. Initially begun in 2019 in support of USMA Senior Rotator faculty pursuing PhD research prior to returning to the academy, it supports DTRA-RDNT focused research by any military student, regardless of the school they are attending. By doing so, DTRA gains greater access to the intellectual capital of the numerous officers not attending a DoD graduate school and the resources within civilian schools, while also providing an independent source of funding for equipment, supplies, and travel. Often students must choose research projects that are funded through their research advisor or academic department based on previously awarded grants, and so are limited in the ability to perform defense-relevant research. The NSERC Fellowship provides greater freedom to officers pursuing Defense-focused projects that align with their interests and can be continued at a service academy upon graduation.

2019 Fellow: LTC William Koch

The first NSERC Fellow was LTC William Koch, an Academy Professor and former FA40 at the US Military Academy conducting research into miniaturization of Time Projection Chamber (TPC) detectors for a Soldier-portable directional neutron detection system. LTC Koch began this work as his Master's thesis at MIT, continuing the project at USMA as a junior faculty member and as a PhD student after selection as an Academy Professor and his return to MIT. He has since returned to USMA where he is continuing the research as a cadet capstone research project to design a functional prototype TPC neutron detector backpack.

One technique for detecting special nuclear material is via the spontaneous fission neutrons produce from the isotopes of either uranium or plutonium. The Department of Defense is constantly seeking the development of the next generation of portable detection systems to support the missions of radiation field mapping and counterproliferation searches. By capitalizing on the historic developments in a typical high energy physics experiment and modernizing the technology, a backpack portable detector can be produced that can fill this capability gap.

A TPC is typically a very sophisticated detector that provides significant information on every interaction. Using modern technology to replace thousands of digitizers with a single digital camera, this technology is now robust enough to be re-imagined in a backpack-scale package. Data collected from a graduate program demonstrate that this technology is functional with a low-power, light weight image intensifier, reducing the power and size constraints to within the limitations of a backpack.

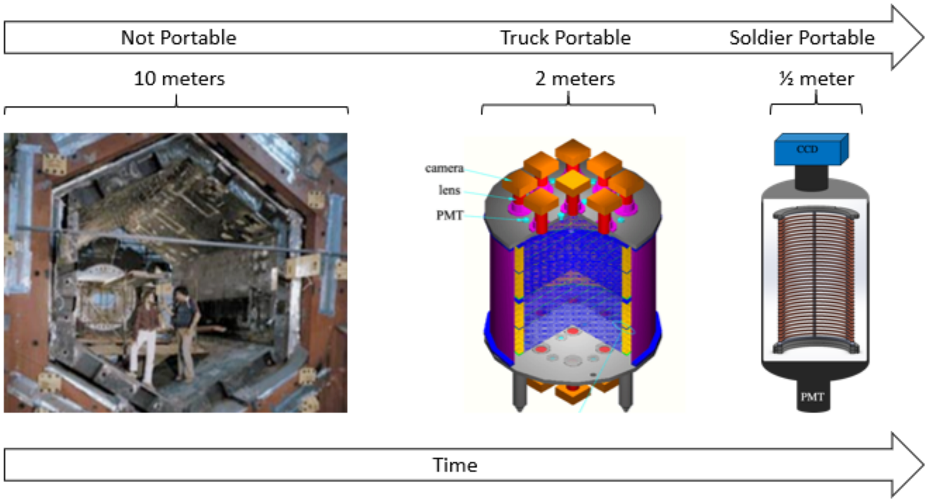

Figure 1. The historic decrease in the size of TPCs, driven by the use of modern Charge-coupled Device CCD cameras, has resulted in TPCs that could feasibly be carried by one Soldier.

Simulations show that a fully portable TPC being operated while carried past a fast neutron source at a deliberate walk can locate the source to within 60 cm on a single pass by a single backpack with a closest approach of two meters. Further, any indication of the source provides a location, so false negatives can simply be studied more closely to confirm or deny the presence of illicit material. [2]

With this setup, each interaction between a fast neutron and target gas nucleus provides a crude direction. As data is collected and the location of an illicit source is determined, the data can be unfolded to provide an energy spectrum of the fast neutron source. This provides the capability to conduct source characterization, distinguishing between more typical neutron sources, such as Californium-252 or alpha-Beryllium neutron sources, and illegal fast neutron sources such as Weapons Grade Plutonium. With this updated technology, an operator can carry this backpack into a search operation to locate and characterize hidden sources of illicit nuclear material with minimal search time. [2]

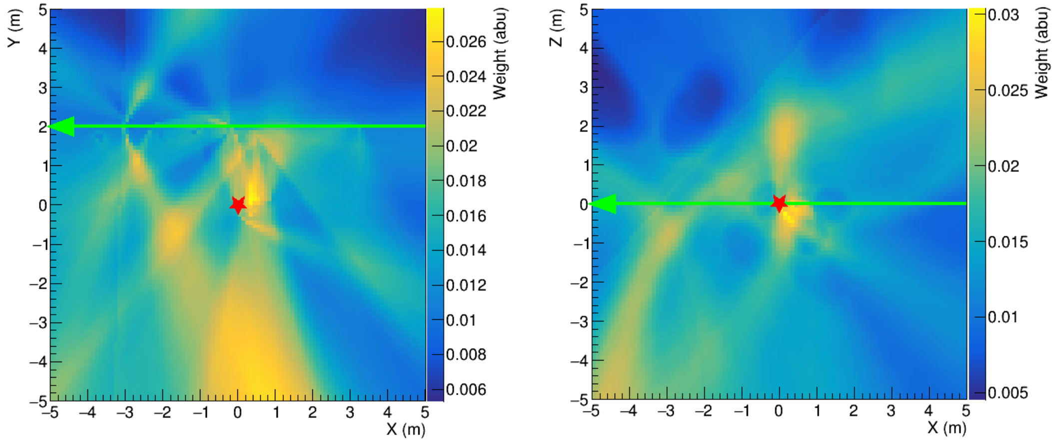

Figure 2. Left, modeled source localization with closest approach of 2 m. Right, modeled source localization with closest approach of 0 m. Modeling shows that source localization can achieved with similar accuracy. [2]

This research is ongoing at USMA with a group of cadets to develop a prototype backpack detector as part of their First Class year engineering design capstone. Testing of this prototype is planned to be conducted at a mobile source user facility. Additionally, cadets will develop a data fusion and analysis tool to support operator situational analysis. Finally, further studies by LTC Koch and USMA cadets will focus on varying the TPC gas mixtures in order to optimize the detector gain.

2020 Fellow: LTC Jacob Capps

The second NSERC Fellow is LTC Jacob Capps, an Academy Professor and former FA52 at the US Military Academy. LTC Capps is currently attending Oregon State University where he is researching heavy inorganic oxide and doped Potassium dihydrogen phosphate (KDP) scintillators for fast neutron detection, including GEANT4 (GEometry ANd Tracking), modeling. The NSERC funded the purchase of detection electronics necessary for data collection, as well as travel to Lawrence Livermore National Laboratory for consultation with GEANT4 specialists on staff. Additionally, USMA cadets Nathaniel Holloway and Louis Alfeld served as summer interns working with LTC Capps during 2021.

LTC Capps research focuses on the optimization of scintillator materials for detection of neutron and gamma particles for the identification of special nuclear material. Heavy organic inorganic scintillators have a very high efficiency for detecting the fast neutrons, but have a high production cost for the scintillator crystals. By creating a composite scintillator material (ZEBRA) using layers of Cerium-doped Gadolinium Orthosilicate (GSO:Ce), Polystyrene, and Polymethyl methacrylate (PMMA), similar neutron detection efficiencies can be achieved at a lower cost.

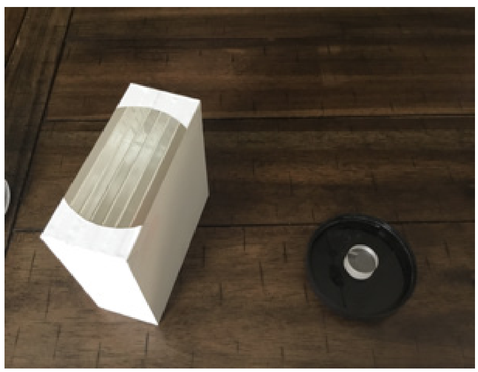

Figure 3. Composite ZEBRA (left) vs. Non-composite (single crystal) Lu2-xGdxSiO5 (LGSO). [3]

LTC Capps has made extensive use of GEANT4, a modeling code for simulating particle transport in matter, to characterize the optical and nuclear response of the ZEBRA composite scintillator. These simulations improved the understanding of the energy deposition, number of neutron interactions, and the index of refraction for the different layers of the ZEBRA scintillator, as well as the number of scintillation photons produced per ionizing interaction. The properties derived from this model were then used to model the Plutonium-Berilium (PuBe) source spectrum measured by the detector. [3]

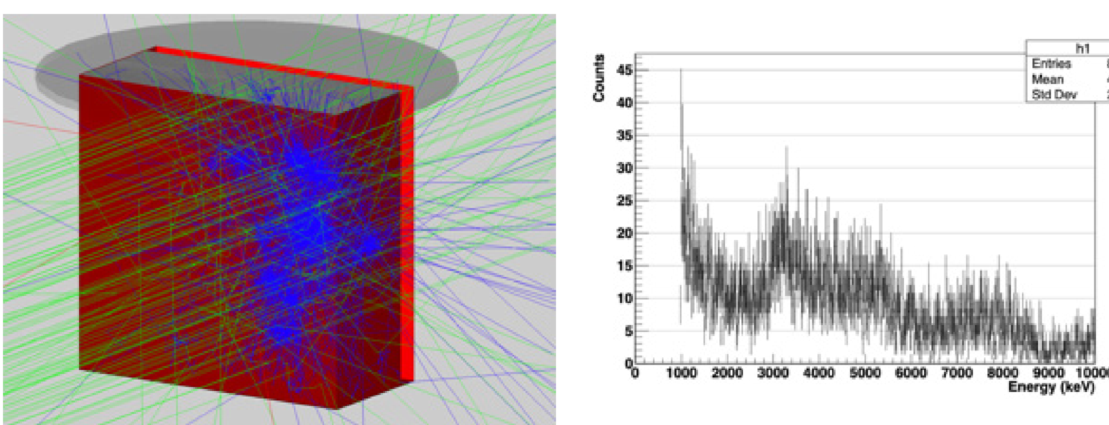

Figure 4. Left, GEANT4 side/top view of GSO:Ce crystal with 100 4.5 MeV neutrons interacting with the crystal face and a PMT located on the top plane. Right, GEANT4 output of the energy spectrum of a PuBe source incident on GSO:Ce of 50,000 events. [3]

Cadets Alfeld and Holloway assisted in the preparatory work for these simulations by developing the model for measuring the light output from the ZEBRA scintillator. Additionally, they performed experiments to determine the optimum photomultiplier and light blocking materials for construction of the experimental apparatus used by LTC Capps to validate the model.

The most recent work by LTC Capps was to experimentally validate the accuracy of the model using an actual ZEBRA scintillator and PuBe source at Lawrence Livermore National Laboratory. Initial analysis of the results found the model to be 96% accurate to the physically real experiment. Future studies will include modeling of alternative channel layer materials and further validation of the model via experiment. [3]

Future NSERC Fellows

The NSERC Research Fellowship program supports research aligned with DTRA Nuclear Technologies mission areas performed by military officers with the intention of continuing that research at their service academy upon graduation and is not limited to any institution or service. This fellowship provides funding to purchase supplies and equipment required to conduct research that will return with the officer to their assigned service academy to continue the research as academic year capstone or independent study projects by cadets or midshipmen. Additionally, NSERC will continue to support the research for the duration of the faculty member's assignment at their service academy.

The NSERC fellowship is open to any military officer interested in performing DTRA-RDNT focused research during their ACS assignment. Officers interested in performing research in the RDNT mission areas are invited to contact the NSERC with a description of their research interests and funding needs. This program is not limited to a specific number of participants, only by the availability of continued funding to support the officer's research program.

NSERC Summer Internships

The largest single program supported by the NSERC is service academy and ROTC summer internships. These experiences provide a research-focused, operationally relevant experience to cadets and midshipman that exposes them to both the nuclear enterprise and the countering weapons of mass destruction mission space. It is intended not only to develop future leaders who are cognizant of and competent in nuclear and CWMD issues, but also to provide real value to the internship sponsor organizations to analyze and understand operationally or strategically relevant problems and provide solutions or recommendations to the organization. Ranging in length from 2 weeks to 2 months, each internship is tailored to offer a learning experience about the nuclear and CWMD enterprise while also providing value to either the host organization or another customer.

Conventional-Nuclear Integration Wargaming at the Naval Postgraduate School and USSTRATCOM

With the increased emphasis on great power competition necessitating the revitalization of conventional-nuclear integration, the NSERC sponsored multiple interns at a handful of locations to work on this problem. Four interns interned with the Naval Warfare Studies Institute's (NWSI) Wargaming Center, a research center within the Naval Postgraduate School, another three interned with U.S. Strategic Command (USSTRATCOM) and the National Strategic Research Institute (NSRI), and a final cadet interned directly with the NSERC.

The interns at NWSI worked through a tailored version of the Wargaming Center's Basic Analytical Wargaming Course, normally offered as a mobile training team or graduate-level course, focused on nuclear weapons employment on the conventional battlefield. The cadets developed a tabletop wargame with guidance from the DTRA RDNT Assessments Division that could be used to educate tactical commanders about nuclear weapons effects on conventional forces and provide a quick and easily iterative means to apply lessons learned and adapt to battlefield nuclear warfare in order to minimize the impact of hostile nuclear employment on friendly forces.

The second group of cadets, working with USSTRATCOM and the NSRI, focused on two different projects. At NSRI, Army ROTC CDTs Hayden Maxwell, Taylor Catlin, and Frank Miele along with a handful of civilian NSRI Strategic Deterrence interns developed a virtual delivery option for NSRI's Limited Nuclear Conflict Tabletop Exercise. Previously an in-person event, the cadets developed a methodology for the wargame that could be used in a fully virtual environment, then implemented this into a complete full-stack web application with supporting materials. This wargame solution was briefed to Lt Gen Thomas A. Bussiere, Deputy Commander, USSTRATCOM and Maj Gen (Ret) Richard Evens, NSRI Director. [4] Meanwhile, CDT Amanda McDonough worked with USSTRATCOM staff to gather unclassified data and real-world strategic and operational understanding of nuclear weapons employment to support an academic year Capstone project at USMA.

Finally, the NSERC hosted Navy ROTC Cadet Catherine Yang to develop an algorithm and graphical interface for a tool to adjudicate nuclear weapon effects on tactical units in a simulated wargame. This tool allows the user to define a unit composition using dismounted infantry, motorized infantry, and tank platoons, each with a defined P50 (pressure for 50% kill probability). The algorithm then determines the radius from ground zero where this pressure would occur, checked if the unit was within that radius, and assessed whether the unit was destroyed. By applying the Monte Carlo analysis technique to perform hundreds of iterations, the algorithm can adjudicate the effects of nuclear weapon employment in a user defined scenario. [6] This research has formed the starting point for a USMA academic year Capstone project, in which cadets will work to implement a more advanced algorithm and integrate it as a plug-in for the Army's OneSAF wargame simulation software.

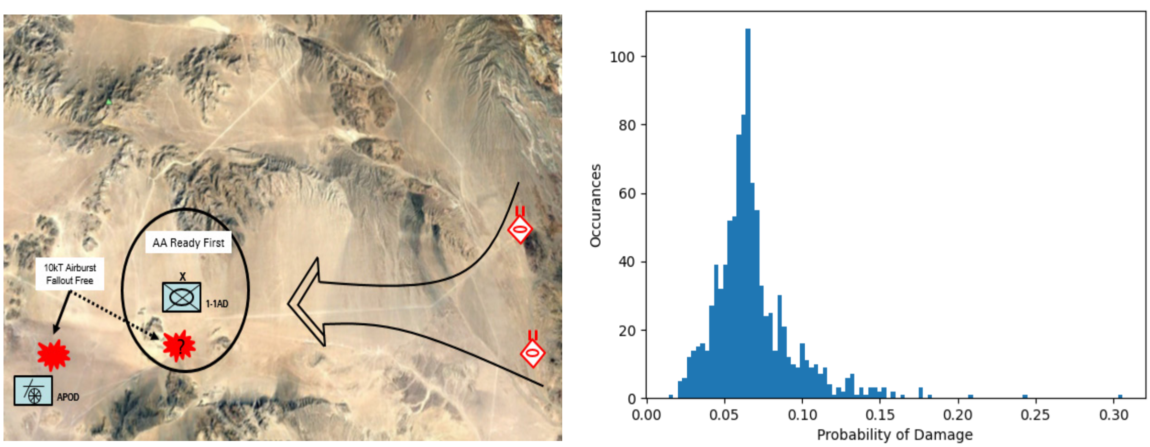

Figure 5. Left, a combined arms company executes a flanking maneuver to attack an enemy force. Each platoon in the company moves at a different velocity and has a different "hardness" against nuclear blast effects. Right, the probability of damage distribution for the infantry platoon determined from 10,000 iterations of the simulation. [5]

Using wargaming as a method to explore the survivability of military formations and the reactions of tactical and operational leaders to the employment of nuclear weapons on the battlefield is an important growth area for the nuclear enterprise, and the NSERC plans to support the development of this expertise within the DoD academic community into the future. The cadet internship program provides an opportunity for sponsor organizations to train junior leaders about their mission and to receive the necessary manpower to work through the questions facing the nuclear and CWMD community in an analytical manner.

Providing Useful Solutions to Real Problems: Interns at USANCA

While the broad problems facing the nuclear and CWMD communities are far too large and complex to solve in a few weeks, organizations often face a deluge of small tasks that require significant dedication of time. NSERC interns have successfully developed solutions to these problems to improve workflows, perform error checking on critical data, and improve the capability of staff officers and leaders to accomplish their mission.

The U.S. Army Nuclear and CWMD Agency (USANCA) has faced significant growth in its mission and influence with the increasing emphasis on nuclear operations within the Army. Two USMA cadets, CDTs Riley Hoyes and Kevin Trajgiel, developed solutions to internal requirements and contributed to important strategic documents for Headquarters, Department of the Army.

CDT Hoyes' project focused on improving the workflow for converting large, consolidated data files from USANCA customer agencies into formatted inputs for processing in nuclear effects models. She developed an R script that receives a single file containing the consolidated data for hundreds to thousands of events and parses this data into individual files. The script also error checks these files to ensure they are correctly formatted for the receiving modeling codes. This scripting project allowed the data processing time to decrease from ~30 minutes to ~1-2 minutes per event. [6]

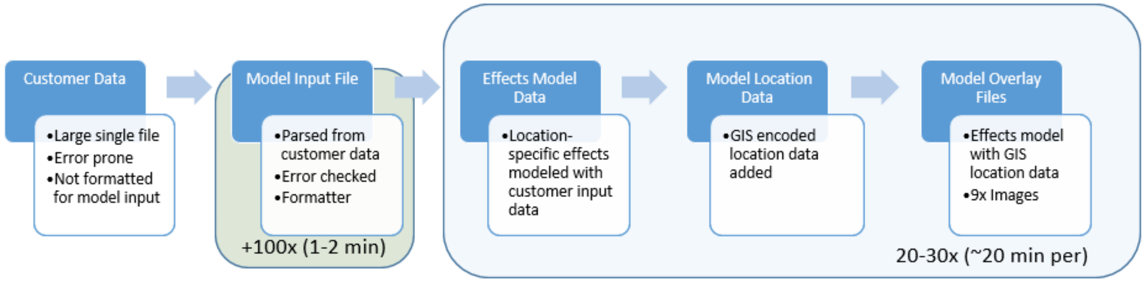

Figure 6. Process Diagram for converting Strike Data to Fallout Model outputs. [6]

CDT Kevin Trajgiel, on the other hand, focused on the emerging strategic documents, such as the Army Biodefense Strategy and the Conventional-Nuclear Integration Strategy, being produced at USANCA. He analyzed these and past strategy documents to identify common themes and priorities to support revising the Army's CWMD Strategy. This project resulted in high-quality staff analysis briefed to the USANCA Director that will directly support the writing of a new Army CWMD Strategy in the near future.

Future Internship Sponsors

The NSERC summer internship program is dependent on the continued support of the organizations and leaders within the nuclear enterprise and CWMD community to host interns and provide intellectually stimulating projects that individual or teams of cadets and midshipmen can work on during their time with the organization. Additionally, successful internships have also involved engagements with senior leaders, other parts of the organization, or training and education to improve the interns ability to contribute to their project. Organizations interested in sponsoring a cadet or midshipman can contact the NSERC to discuss the projects available, timeframe for the intern, and any limitations or constraints such as clearances.

Notes

1. Defense Threat Reduction Agency. "Defense Threat Reduction Agency" Accessed August 11, 2021, https://www.dtra.mil/.
2. Koch, William L. "Backpack Portable TPC". Presentation to DTRA NSERC. August, 2021.
3. Capps, Jacob W., Smith, Craig F., Schellman, Heidi M. "Modeling and Characterization of Composite Scintillator Design". Report to DTRA NSERC. September, 2021.
4. Ideus, Katelyn. "NSRI strategic deterrence interns present transformed wargame, experience to USSTRATCOM leaders." National Strategic Research Institute. Accessed September 16, 2021. https://nsri.nebraska.edu/news/news-releases/2021/08/nsri-strategic-deterrence-interns-present-transformed-wargame-experience-to-usUSSTRATCOM-leaders
5. Yang, Catherine. "Integrating Nuclear Effects into Wargame Simulations". Presentation to DTRA NSERC. August 20, 2021.
6. Seybert, Adam. "Cadet Summer Research". Presentation to DTRA NSERC. September 8, 2021.

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Ideus, Katelyn. “NSRI strategic deterrence interns present transformed wargame, experience to USSTRATCOM leaders.” National Strategic Research Institute. Accessed September 16, 2021. https://nsri.nebraska.edu/news/news-releases/2021/08/nsri-strategic-deterrence-interns-present-transformed-wargame-experience-to-usUSSTRATCOM-leaders

Yang, Catherine. “Integrating Nuclear Effects into Wargame Simulations”. Presentation to DTRA NSERC. August 20, 2021.

Seybert, Adam. “Cadet Summer Research”. Presentation to DTRA NSERC. September 8, 2021..

United States Military Academy Cadets in the Department of Chemistry and Life Science complete laboratories in many of their required courses and also engage in faculty-mentored independent research projects. Since 2018, Cadets have been co-authors on over 45 peer-reviewed publications. Cadet research enhances their STEM education and enables Department of Chemistry and Life Science Cadets to be successful and win multiple national competitive scholarships every academic year.

Reinvigorating a Technical Countering Weapons of Mass Destruction Distance Learning Graduate Certificate Program

Dr. James Petrosky, Dr. Gaiven Varshney, Dr. Jeremy Slagley
and Ms. Sara Shaghaghi

Air Force Institute of Technology

Current Countering Weapons of Mass Destruction (CWMD) demands can be divided broadly into policy and science. The science of chemical, biological, and radiological/nuclear weapons informs the limits of development, production, employment, operation, detection, risk characterization, human and material protection, and medical intervention. In short, the science of weapons of mass destruction (WMD) should precede and inform the development of policy. It is to this end that the Air Force Institute of Technology (AFIT) CWMD program was re-established, providing a technical educational option for practitioners to understand the science behind a very technically challenging subject.

THE PAST

Graduate educational programs can focus on either science or policy. Since the AFIT graduate school is focused on technology-based education, it was only fitting that AFIT developed and operated the science-based graduate certificate program in CWMD for nearly a decade. The initial program was developed for United States Air Force (USAF) scientists that had a background in a technical field but were assigned to organizations that required integration of chemical, biological, and nuclear protection. In its later years, however, the program was primarily supported by Army functional area(FA) 52 counterproliferation officers. Due to low enrollments the program was sunset

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Dr. Jeremy Slagley, Lt Col (Ret) is the Director of the Countering Weapons of Mass Destruction Graduate Certificate program at the Air Force Institute of Technology, on Wright-Patterson AFB, OH. He has a B.S. in Environmental Engineering from the US Military Academy at West Point, NY, an M.S. in Industrial Hygiene from the University of Iowa, and a Ph.D. in Occupational Safety and Health from West Virginia University. He served 20 years as an Air Force Bioenvironmental Engineer officer. His email address is jeremy.slagley@afit.edu.

Ms. Sara Shaghaghi is a Teaching Assistant for the Countering Weapons of Mass Destruction Graduate Certificate program at the Air Force Institute of Technology, on Wright-Patterson AFB, OH. She has a B.S. in Chemical Engineering from the University of Dayton, an M.S. in Bioengineering from the University of Dayton, and is working on her Ph.D. in Systems Engineering at AFIT. Her email address is sara.shaghaghi@afit.edu.

in 2018.

THE PRESENT

In 2020, with a renewed interest in CWMD operations, the Department of Homeland Security (DHS) CWMD office sought to establish a technical CWMD expertise development program and turned to AFIT to re-establish the technical CWMD certificate program. Following substantial coordination and assurance from DHS that program funding was in place, AFIT began planning and coordination to re-establish the CWMD certificate program. During the COVID lockdown in 2020, AFIT AFIT restarted the program through the recently established Nuclear Expertise for Advancing Technologies (NEAT) Center[1] and recruited and enrolled students from the Air Force, Army, and Lawrence Livermore National Laboratory (LLNL) for the October 2020 start. In September 2021, the first 30 students were awarded their graduate

Dr. Gaiven Varshney (co-chair and CHEM 597 instructor) and Dr. Anna Bucy (CWMD administrative assistant) prepare the first 30 graduate certificates for mailing.

certificates in CWMD.

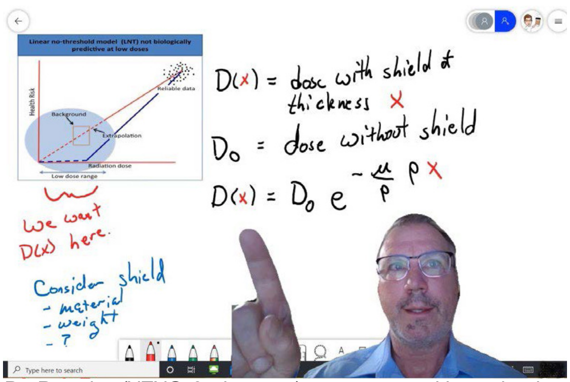
The AFIT CWMD program is shared by the Departments of Engineering Physics and Systems Engineering & Management. The program is housed in the NEAT Center, headed by Dr. James Petrosky. The NEAT Center is a technical partner and a bridge for developing technical talents and human capital for mission partners focused on protecting the US. NEAT is engaged in research, education, and publication that enhances Defense, Air Force, and Department of Energy organizational cross-knowledge. The education strategy offers a broad portfolio of courses and programs oriented toward technical nuclear subjects, including technically oriented nuclear forensics graduate courses and research that develops national level expertise of interest for key mission partners. The close ties between education and research and national security efforts are clear, making AFIT a primary institute for innovation and relevance.

Several changes were necessary for the program reestablishment to broaden the student population. These included adding material on biological effects and physiology, which is of increased interest due to the current pandemic. Additionally, there was an effort to rebuild the program with a consistent format and structure, following AFIT's extremely popular Nuclear Weapons Effects, Policy, and Proliferation (NWEPP)[2] graduate certificate program. This structure has proven to provide the best flexibility for students who must balance their primary duties with distance learning education, while providing interactions between faculty and students at the graduate level. Content changes also included some reorganization of materials to provide similar approaches to common materials, such as application of mathematical models for prediction of outcomes and using common software such as ExcelTM.

The program maintained the focus on basic and applied sciences behind each of the CWMD topic areas but brought new subject matter related to consequence management to the forefront. The substantial faculty experiences on the broad applications of CWMD, both military and civilian, represent over 100 years of biowarfare, chemical and nuclear weapons, and physiological response technical expertise. This experience led to the assembly of valuable and applicable course materials, and many real time conversations during webinars and office hours. Together, these resulted in many relevant lectures, and discussions related to students' current work areas. The students ranged from PhDs to new Lieutenants, and from CWMD researchers to CWMD responders.

The Biological Weapons Effects and Technology course materials were especially relevant against a backdrop of an international pandemic. Many students commented on the specific relevance and daily applicability of the course materials, for both scientific studies and development of policy. The course covered technical aspects related to infectious disease epidemiology, biological agent production methods and history of use, and characteristics of bio-pathogens that lend to weaponization.

The Chemical Weapons Materials, Effects, and Technology course included an intense organic chemistry review and a basis for the complex methods for creating chemical weapons. The course then covered how chemical weapons are employed, the process by which chemical weapons can cause harm, the technical issues associated with detection and decontamination of chemical weapons, and the selection criteria for choosing a chemical weapons route.



Dr. Petrosky, (NENG597 instructor) presents a webinar related to shielding methods.

The Nuclear Weapon and Radiological Effects course included an understanding of radiation and how it is transported through various environments. The course presented students with various web available references to determine exposures and shielding effects in order to survive a radiological incident or attack. The course was completely re-written to focus on domestic radiological events with some historical context. This change made this course uniquely different from other “targeting” oriented nuclear courses at AFIT.

The Physiological Effects of CBRN course (which is expected to be the final course in the certificate) explored human physiology relevant to WMDs, covering major organ systems anatomy and physiology. The students selected a particular agent and conducted a focused study on it using the previous course materials as support. This course engaged students via individual and team projects in order to apply the course materials and establish networks among students.

The project-based approach in the final course in the certificate supported the goals of integrating the science, having knowledge of the current literature, and informing policy decisions. These goals are a unique aspect of the AFIT CWMD program. Unlike training, graduate education requires students to analyze and evaluate the information in order to make assessments and decisions. This is enhanced by faculty led student projects and evaluation and feedback on the topic. Students’ innovative ideas emerge and are rigorously examined and the scientific process is applied multiple times to hone skills.

THE FUTURE

Thanks to the Department of Homeland Security CWMD office’s continued support, AFIT has expanded offerings of the CWMD program into 2022. The program will be able to offer multiple offerings of courses and substantially increased enrollment. This expansion will allow AFIT to reach more organizations and bring in a broader group of students. This expansion is no small measure, as our experience with having students from outside of the DoD, including DHS, NNSA, and LLNL, substantially enriches the course interactions and led to an improved program. The current expansion includes students from Air Force, Army, Navy, NNSA, LLNL, and FBI; all part of the national CWMD team.

Additionally, we are seeking changes to course content to include more information on the “countering” aspect of WMDs and including this into the project work and discussions. We are seeking ways to include this in a consistent way across all courses. Lastly, we are looking to build “step up” course materials to provide students with natural science and math skills, and problem-solving techniques before starting the program. These are being done to ensure student success and enhance learning as many students have not used these skills for some time. Lastly, based upon the huge student and organizational interest, we are seeking to reestablish the CWMD Master of Science (MS) distance learning graduate degree program, which will include the CWMD certificate courses. If your organization may be able to sponsor this program, contact us at CWMD@afit.edu.

THE CWMD GRADUATE CERTIFICATE PROGRAM

The CWMD graduate certificate program is hosted by AFIT's NEAT Center, within the AFIT Graduate School of Engineering and Management. The program is shared by AFIT's departments of Engineering Physics and Systems Engineering and Management. The CWMD program includes four courses delivered via distance learning modality. The courses all include remote asynchronous content delivered via CANVAS learning management system, and weekly synchronous webinars. Each course represents four graduate quarter credit hours (a total of 16 credits for the certificate) and these credits can be used in certain approved master's programs as transfer credits. The intent is for the program to be completed by non-traditional students part-time in one year.

CWMD Certificate Courses

- BIOL 597 Biological Weapons Effects and Technology
- CHEM 597 Chemical Weapons Materials, Effects, and Technology
- NENG 597 Nuclear Weapon and Radiological Effects
- CWMD 596 Physiological Effects of CBRN

Admission requirements:

- A Bachelor's degree in a science, engineering, or medical related field (Physics, Biology, Chemistry, Nuclear Engineering, Industrial Hygiene Environmental Science, Physiology, or Epidemiology)
- College algebra required and calculus is desired with a grade of C or better.
- A cumulative undergraduate GPA of 3.0 (on a 4.0 scale).
- US Citizenship

Waivers to the above criteria may be granted on a case-by-case basis. Therefore, those who do not meet the above criteria are encouraged to apply.

More information is available at: https://www.afit.edu/EN/programs.cfm?a=view&D=21 or contact us by email: CWMD@afit.edu.

Notes

1. Nuclear Expertise for Advancing Technologies Center – focused on building and enhancing careers on DoD technical subjects.
2. The Nuclear Weapons Effects, Policy and Proliferation graduate certificate program includes 3 weekly lessons followed by a live webinar.

How to Submit an Article to the

Countering WMD Journal

The Countering WMD Journal is published semi-annually by the United States Army Nuclear and Countering WMD Agency. We welcome articles from all U.S. Government agencies and academia involved with CWMD matters. Articles are reviewed and must be approved by the *Countering WMD Journal* Editorial Board prior to publication. The journal provides a forum for exchanging information and ideas within the CWMD community. Writers may discuss training, current operations and exercises, doctrine, equipment, history, personal viewpoints, or other areas of general interest to CWMD personnel. Articles may share good ideas and lessons learned or explore better ways of doing things. Shorter, after action type articles and reviews of books on CWMD topics are also welcome.

Articles submitted to *Countering WMD Journal* must be accompanied by a written release from the author's activity security manager before editing can begin. All information contained in an article must be unclassified, nonsensitive, and releasable to the public. It is the author's responsibility to ensure that security is not compromised; information appearing in open sources does not constitute declassification. The *Countering WMD Journal* is distributed to military units and other agencies worldwide. As such, it is readily accessible to nongovernment or foreign individuals and organizations. A fillable security release memorandum is provided at http://www.belvoir.army.mil/usanca/.

The *Countering WMD Journal* is published twice a year: Fall/Winter (article deadline is typically 15 September) and Spring/Summer (article deadline is typically 15 March). Send submissions via email to usarmy.belvoir.hqda-dcs-g-3-5-7.mbx.usanca-proponency-division@army.mil, or as a Microsoft Word document on a CD via mail, to: Editor, CWMD Journal, 5915 16th Street, Building 238, Fort Belvoir, VA 22060-5514.

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