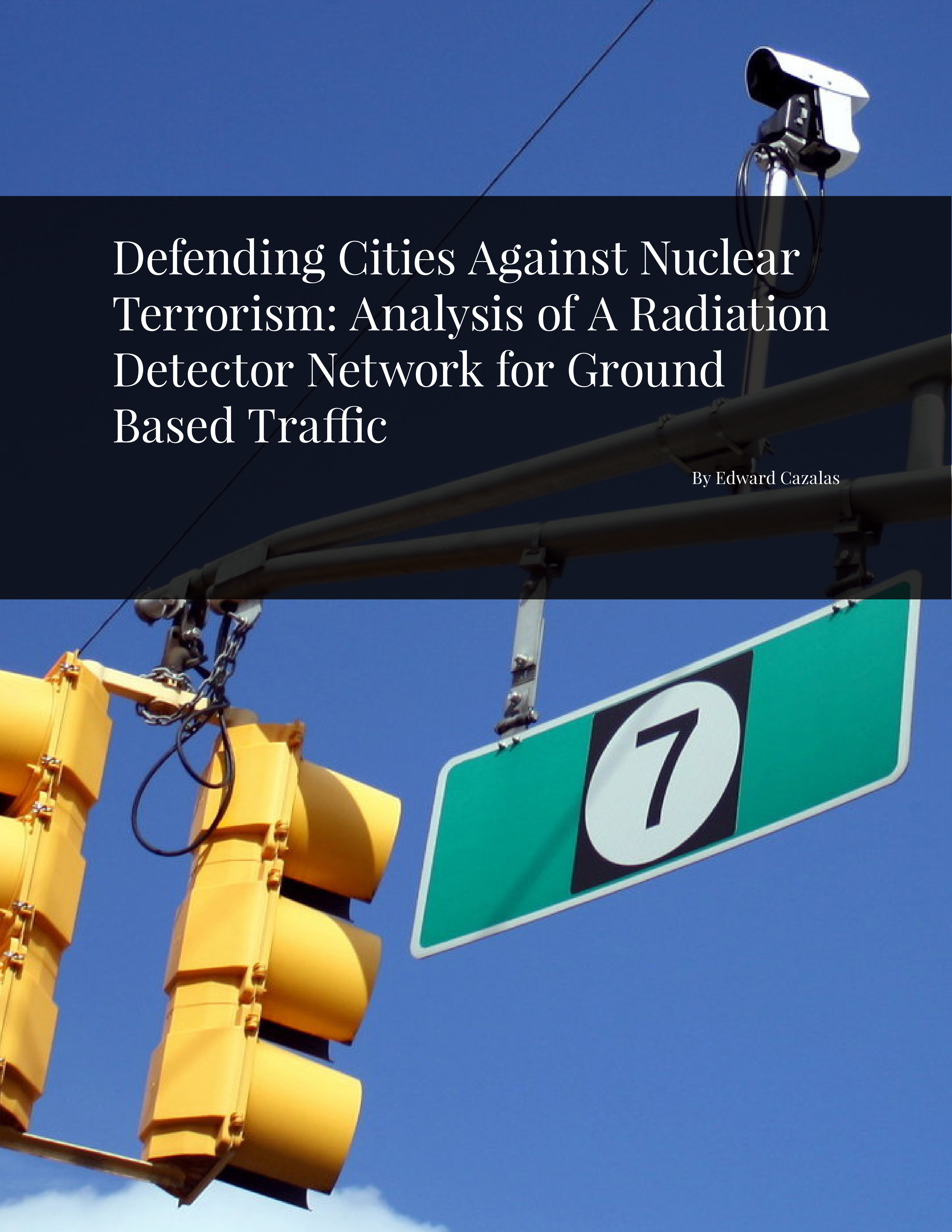
Defending Cities Against Nuclear Terrorism: Analysis of A Radiation Detector Network for Ground Based Traffic

By Edward Cazalas



Abstract

This article describes a specific, promising concept for a traffic-based radiation detector network concept deployed on roads/highways/stoplights/etc. The detector network concept is intended to help defend urban areas against nuclear attack by adversaries. The network has two potential functions: to detect and localize the covert transport of nuclear materials or weapons (specifically plutonium-based), and to monitor nuclear fallout in post-attack scenarios. This work analyzes the basic technical feasibility of the network, including detector hardware, deployment, and detection statistics. It will provide an overview of efforts to defend against nuclear terrorism and to develop concepts related to networked detection. Finally, the article discusses considerations that may affect the policy of the development and deployment of such a system. Included in these considerations is a rough-order-of-magnitude estimate of the cost of detector system deployment, a brief examination of the potential benefits and drawbacks of the radiation detector network, and a review of other concepts that could be, or are currently employed for nuclear detection.

Suggested Citation

Cazalas, Edward. "Defending Cities Against Nuclear Terrorism: Analysis of A Radiation Detector Network for Ground Based Traffic." *Homeland Security Affairs* 14, Article 10 (December 2018). https://www.hsaj.org/articles/14715

Introduction

The threat of nuclear terrorism has loomed over the United States and the international community for decades. World leaders, U.S. Presidents, and politicians spanning time, geography, political rank, and party recognized this threat as serious. Nuclear weapons or materials for a weapon may originate from countries that hold nuclear weapons, have nuclear weapons programs, or operate internal enrichment or reprocessing facilities. Radiological materials, on the other hand, may be accessed from devices or facilities that utilize radiological isotopes, including blood irradiators and therapy tools in hospitals, well loggers, or thermoelectric generators. Bad actors may weaponize highly enriched nuclear material into improvised nuclear devices (INDs) capable of great destruction or weaponize radiological material into radiological dispersal devices (RDDs). Either can be utilized to attack governmental or financial centers, populace, or critical infrastructure. The consequences of a nuclear weapon or IND detonation could be substantially higher, compared to the use of an RDD, in terms of lives lost, damage to infrastructure, spread of radioactive fallout, and subsequent disruption to the economy.[1] It is for this reason that the author emphasizes the examination of nuclear materials, rather than radiological materials, in this work.

Here, we will examine a specific concept to aid nuclear threat interdiction by detecting nuclear weapons or INDs being smuggled into a city. The concept also aims to augment consequence management by measurement of post-detonation fallout radiation. The concept involves a methodology of threat detection that relies on the placement of radiation detectors, in a networked fashion, along roadsides, highways, intersections, etc. We will discuss the prior work conducted in this area and the efforts of various government agencies in dealing with the threat of nuclear terrorism. We will investigate the technical feasibility of this concept by utilizing calculations and simulations, which will provide insight into the concept's effective application and its shortcomings. The article will also discuss cost considerations, benefits and drawbacks of such a concept, as well as alternative concepts that are in place or could be incorporated. Finally, future work will provide guidance on what additional efforts should be undertaken.

Current Efforts at Preventing Nuclear Terrorism

In order to reduce the risk of attack by a nuclear weapon, homeland security authorities utilize a layered defense system. This type of approach focuses on reducing the quantity and number of locations of source materials, while strengthening the physical security of remaining sites.[2] International efforts along these lines have included the Global Threat Reduction Initiative (GTRI), which was established within the National Nuclear Security Administration (NNSA) under the Department of Energy (DOE). These efforts have helped to improve the security of nuclear facilities, processes, and materials outside the U.S. These improvements included upgrading security of nuclear facilities, disposal of surplus fissile materials, strengthening regulatory and inspection regimes, and providing detection and interdiction capabilities.[3]

Meanwhile, the Global Nuclear Detection Architecture (GNDA), which is coordinated by the Domestic Nuclear Detection Office (DNDO) of the Department of Homeland Security (DHS), has improved capability to detect nuclear materials smuggled into the U.S. In cooperation with agencies such as U.S. Customs and Border Protection (CBP), the U.S. Coast Guard, and the NNSA, for example, the DNDO administers the detection and interdiction regime to reduce the risk of nuclear attacks by the non-destructive assay and physical inspection of cargo, vehicles, and persons travelling into the U.S. through ports, airports, or border crossings.[4]

Despite the on-going efforts to secure and intercept nuclear material, the risk remains that these threat materials could still be accessed, smuggled, and utilized in an attack, due to substandard security and the existence of rogue actors. The growth and possible spread of terrorist ideologies to countries with access to nuclear materials or weapons underscores the significance of this threat.[5]

Introduction to a Networked Detector Concept

Detection of threat materials typically relies on detection of radiation, notably gamma-rays and neutrons. The detection of nuclear materials is complicated by the many potential entryways or transport modes available for smuggling.[6] Additionally, the radiation signals detected from these materials are relatively weak and especially difficult to detect at distance. For example, the neutron emission from a HEU (highly enriched uranium) -based weapon would be equal to the level of ambient background neutrons for a detector measurement less than two meters away. While the gamma-ray emissions from a HEU-based weapon are of relatively high energy and intensity (compared to a Pu-based weapon), they are easily shielded by a few centimeters of lead.[7] Further absorption and scattering of the emitted neutrons and gamma-rays takes place by surrounding hydrogenous mediums, air between the weapon and detector, and the transport vessel's or vehicle's steel or aluminum siding. Often, the technical difficulties are magnified by operational constraints, such as the demand for speedy cargo throughput at seaports.[8]

This article will examine the potential of detectors to identify and track nuclear weapons or weapon materials. The detection of nuclear materials could play a role in thwarting such attacks as part of an integrated defense concept. We will describe a network concept for detecting the local transport of such materials within an urban area. If integrated with appropriate operational responses, such a network might interrupt an attack, or even deter its attempt due to its presence. This research shows that a network of these detectors may be able to offer some performance against a Pu-based weapon unless the weapon is highly shielded.

The concept of detector networks has been identified to enhance both detection and, as discussed below, consequence management.[9] Detector networks combine many individual detector nodes that are geographically dispersed with each detector capable of sharing information with each other or with a central processing node.[10] These networks have the potential to serve multiple roles including detection for counter-smuggling, pinpointing a location of attack, and post-blast fallout monitoring. The ubiquity of detectors in a network may increase detection of nuclear materials by preventing an adversary from detouring around known checkpoints at borders and ports. Additionally, the ability of the detector network to pinpoint attack location and monitor fallout would aid emergency response and enhance consequence management.

Consequence Management after a Nuclear Detonation

Obviously, the prevention of such attacks is the focus of many efforts. But prevention may fail, and coping with the consequences of an attack present challenges as well. Fallout from a nuclear weapon may cause prompt radiation poisoning, as well as increasing lifetime cancer risk for those exposed to intermediate-to-high dose levels. Consequently, the radioactive debris would restrict the operational deployment of emergency-response personnel and resources in the area of the blast site and downwind. This places a priority on understanding the distribution of such radioactive debris. Currently, the primary method of assessing the dose and providing information for decision making is to combine information from radiation pagers carried by emergency-response personnel with computational models that consider the location of the blast, local geography, and weather conditions.[11] Unfortunately, this approach places emergency-response personnel at risk and can waste time, by potentially requiring the redeployment of resources which have inadvertently entered or find themselves in higher dose areas, and may waste resources, by requiring personnel who have acquired administrative dose limit levels to be restricted from activity in potentially radiation-contaminated regions and requiring decontamination of personnel and equipment.[12]

The concept of consequence management plays an increasing role for state and federal agencies in response strategies for mitigating the risk of nuclear terrorism.[13] Consequence management may be aided by efficient and informed decision-making for the deployment of emergency-response personnel and resources.

The specific network described in this article is a concept that may provide a means to gather the real-time assessment of dose from fallout across a city or geographic region that can aid decision making for the deployment of emergency response personnel and resources. Together with the network's potential to detect or deter covert transport of some weapons, the concept explored within this article appears promising and justifies further detailed analyses that investigate topics such as placement and density of detectors in a network; who operates, supports, and manages the detector network; and what procedures should be carried out by local, state, and federal authorities in the instance of detection.

Description of a Traffic-Based Detector Network

The detector network is made up of many detector nodes that are, ideally, deployed at an existing traffic-monitoring device location, such as locations of speed or stop-light camera systems. Unlike some other detector network concepts, the network concept described here is intended to be in place and operational well before a search for a nuclear weapon is undertaken or a nuclear detonation takes place. Pairing the detectors with traffic-monitoring devices will allow information from the detector and traffic-monitoring device to be fused (or correlated). Also, communication and electrical power may be accessed through existing feeds that supply communication and power to the existing traffic-monitoring devices. The detectors may be deployed across a city adjacent to roads, highways, on/off-ramps, intersections, or construction zones. Each detector node communicates to a central node that can process and fuse detector information, such as count rate, radiation type, time, and detector location, with information from the traffic-monitoring device, such as photographs of the vehicle, license-plate information, or speed and direction of travel.

Nuclear Material Model in a Detector Network Scenario

Figure 1 shows an illustration of a scenario of a threat vehicle passing by a single detector node paired with a traffic-monitoring device. The radiation detector detects neutrons and is installed under the highway signs, as in Figure 1a. As the threat vehicle, which contains a WGPu (weapons grade Pu) weapon drives toward, under, and away from the detector, the detector neutron measurement displays the presence of neutron-emitting material, as shown in Figure 1b. The detection of an amount of neutrons above a predefined threshold triggers the traffic-monitoring device to activate (photograph), as displayed in Figure 1c. If the detector neutron measurement exhibited an exceptionally large amount of neutrons above background, information from the traffic-monitoring device could be used by local authorities to interdict the vehicle. Otherwise, an additional detector measurement may be taken if the vehicle travels by a second detector node to verify the initial detector reading, and information from the second traffic-monitoring device can be used to corroborate the identity of the threat vehicle.

The probability of detecting a threat vehicle is, in-part, a function of conditions that may be out of the control of those designing or operating the detection network. Conditions such as the route taken to the destination and traffic or road conditions can affect the detection probability in a stochastic manner. Primarily, however, detection probabilities increase for a growing number of detector nodes encountered on a given route, reduced distance between the threat vehicle and detector, and increasing time spent in the vicinity of a detector. Hence, the network's effectiveness would be improved if detector nodes were located at choke points, like bridges, or where vehicles are necessarily slowed, like intersections or on/off-ramps. The puzzle of where to place a limited number of detectors to cover a wide possibility of routes to maximize the overall detection probability of the network is a challenging task. This task is not researched here but is an active area of study.[14]

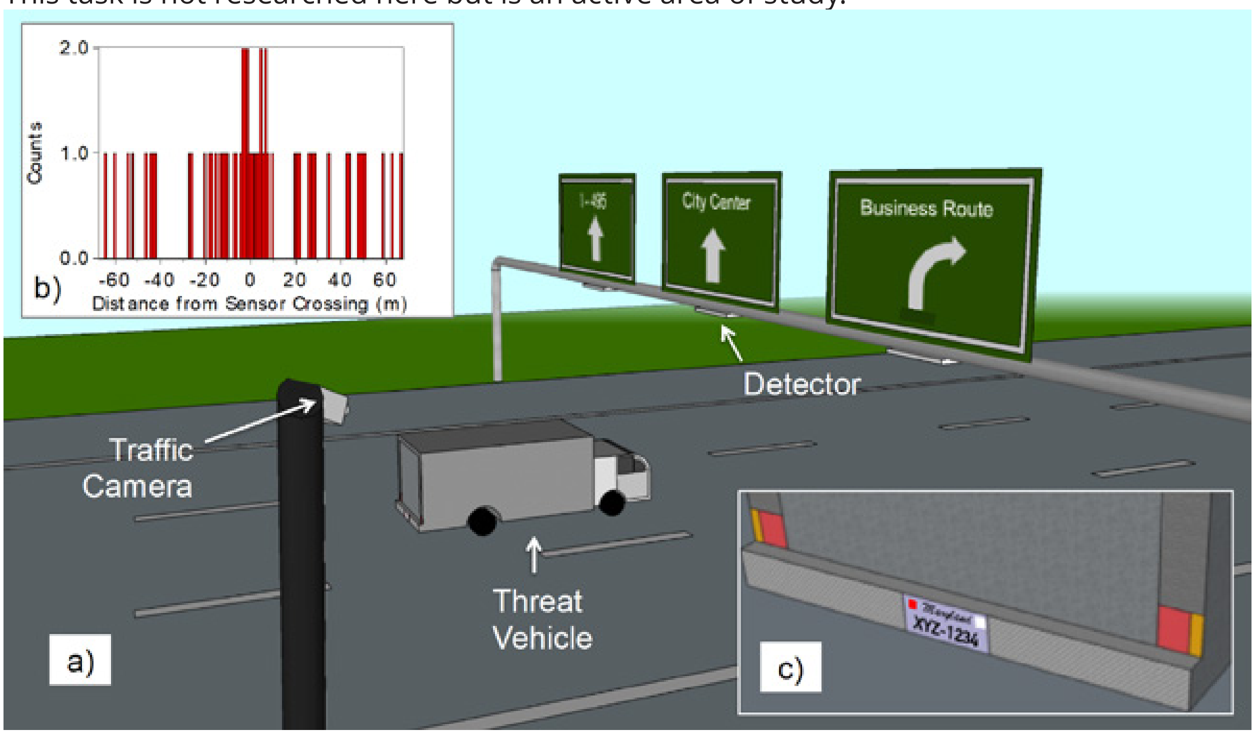


Figure 1: a) A scenario of a vehicle containing threat material (Pu-based weapon) passing by a traffic-monitoring device (traffic camera) and under a radiation detector. b) The neutron measurement of the detector as the threat vehicle travels toward, under (at distance = 0 m), and away from the radiation detector. c) The traffic-monitoring device provides additional information of the threat vehicle, such as a photograph of the vehicle or license plate, or speed information.

A distinct scenario from nuclear materials detection and interdiction is that in which a nuclear attack has already taken place. In this scenario, reliable information of dose as a function of geography and time is important to prevent sending emergency response into high-dose areas. Detector nodes in the blast radius would be destroyed and power may be lost to otherwise operational detectors. However, installing batteries with the detector nodes can mitigate loss of power. Other detonation effects, such as the blast, thermal radiation, and electromagnetic pulse effects will have impact on the operational survivability of the nodes within the network. It is not expected that the addition of batteries will mitigate these effects to individual nodes, as these effects will likely also damage beyond operability the more fragile radiation detection equipment of an affected node before reducing battery performance. Thus, the addition of a battery is to provide power in the event of grid-wide power loss. The information provided by the detector network may be utilized by emergency-response personnel for assessment of radiation-dose levels at node locations and the time and dose evolution of fallout due to weather conditions across a geographical area of the detector network. This information may aid in the decision making regarding the deployment of emergency personnel and resources via roads and highways or provide information to guide possible public alerts for sheltering or evacuation.

Prior Work

Research into general detector networks has recently gained momentum through the Defense Advanced Research Projects Agency (DARPA), under the Department of Defense (DOD), and the DNDO. DARPA recently funded (as of 2014) the SIGMA program, which aims to spur the development of lower cost, more capable detectors. These detectors may be deployed in a ubiquitous or networked fashion and enable the enhancement and development of new concepts-of-operation to counter nuclear terrorism.[15]

A more direct parallel to the study undertaken here is the recently completed work by DNDO (ending in 2014) on the Intelligent Radiation Sensing System (IRSS) that attempted to develop technologies to determine the location of a radiation source through networked portable detectors.[16] DNDO has also funded work (since 2014) on the Radiation Awareness and Interdiction Network (RAIN). RAIN has the goal of developing technologies for monitoring for radiation sources in free-flow traffic fused with other detectors, such as video cameras or license plate readers. To date, it appears that technical analyses from these projects have largely focused on specific technology development or statistics-based analysis of network systems. While some literature exists focused on the specific aspects of technical feasibility, limiting operational considerations, or policy implications of a radiation-detector network, these publications rarely consider the overlap of all these aspects, particularly for a concept combining the roles of both detection and fallout monitoring. Herein, the overlap of these aspects is considered.

The concept of a network for detection and location of nuclear materials has been studied from the aspects of detector hardware and experimentation,[17] detection and localization statistics,[18] communications between detector nodes or with a central processing node,[19] and operational concepts.[20] One such study investigated a concept that involved the deployment of detectors into personal vehicles to be scanned at scan stations similar to tolling stations.[21] While deployment of a detector onto a personal vehicle would extend the integration time of the detector and enhance the proximity of the detector to potential threat materials, a difficulty of the concept is in having public acceptance of invasive monitoring of personal property and susceptibility of the detectors to removal, spoofing, or sabotage. There is an existing literature on policy-related aspects such as preventing nuclear terrorism,[22] and measuring the effects of a nuclear blast in a city.[23]

The concept analyzed in the paper herein does not rely on invasive deployment into personal property. Moreover, it can employ logistics of maintenance already in existence for traffic-monitoring systems. Additionally, the detectors deployed in the entailed concept are less susceptible to sabotage, especially when attached to above-road signs. While deployment of detectors on a roadside (on the ground) would present a higher potential for sabotage, failures of or abnormal readings from individual detector units may be quickly recognized through existing communication networks and addressed.

Analysis of the Technical Feasibility of Detection

The detection of radiation emitted from nuclear materials involves the absorption of gamma-rays or neutrons in the detector medium. Gamma-ray detection relies on the absorption of the gamma-ray energy, whereas neutron detection typically relies on the thermalization of neutrons through scattering in a hydrogenous medium in order to enhance absorption by isotopes such as ^{10}B or ^{6}Li, for a converter-style detector.[24] Once the neutron is absorbed, the energy of the reaction particles is absorbed in the detector medium forming a detection event. It is possible for a detector to detect both gamma-rays and neutrons. Analog electronics or digital algorithms such as pulse height or pulse shape discrimination are utilized to distinguish the difference. To model accurately the number of detection events in a given detector medium, it is first necessary to determine what materials (and subsequent emission type and energy spectrum) should be considered for modeling and then to model the emitting source and intermediary media. Finally, the number of energy-depositing absorption events may be calculated for a detector of a given detection medium thus facilitating the evaluation of the efficacy of a detector system.

Difficulties of Detecting Nuclear Materials

Detection and interpretation of gamma-ray signals are typically easier than that for neutrons, due to the detection equipment used, relative ease of obtaining spectrographic information from gamma-ray detection, the need for radiation-type discrimination in neutron detection, and use of thermalization mediums for neutron detection.[25] However, gamma-ray detection of threat materials is complicated by the much higher prevalence of gamma-ray emitting, naturally occurring radioactive materials (NORM), such as bananas (^{40}K) or cat litter (^{232}Th decay chain). NORM may cause unacceptable rates of false alarms in detector systems or may be utilized to mask the signal from threat materials. Additional complications are added due to the relative ease of gamma-ray shielding, which may be accomplished with a few centimeters of high-Z materials such as lead and unavoidably by the frame and siding of vehicles. Finally and importantly, the signal received by the detector from a threat source may be masked by gamma-ray background radiation, which is approximately an order of magnitude higher for gamma rays than neutrons.[26]

Considering alone the relative difficulty of gamma-ray detection (*vs.* neutron detection) of a nuclear weapon in the presence of background radiation, a 'back-of-the-envelop' calculation is performed, with results in Table 1. The calculation 1) assumes a number of emitting gamma rays and neutrons from the surface of a weapons grade U (WGU) and WGPu weapon source; 2) determines the number of gamma rays or neutrons that reach a detector surface by estimation of the source-detector solid angle; and 3) compares the number of gamma rays and neutrons reaching the detector surface to the background radiation at the detector surface by the respective radiation type. The calculation does not consider absorption of radiation in air, as this is assumed negligible, or the detection efficiency of the detector, as it is assumed that the detection efficiency of signal and background of a given radiation type are similar. Table 1 shows the low number of gamma rays that may be detected relative to background. Table 1 also shows the low number of neutrons that may be detected from WGU relative to background, and the high number of neutrons that may be detected from WGPu relative to background. Partially given the results of Table 1 and the other complications of gamma-ray detection, this study will investigate the efficacy of a detector system for detection of WGPu.

Table 1: The results of a calculation considering emission of neutrons and gamma rays from the surface (labeled 'Surface') of a weapons grade U weapon (WGU, 12 kg) and a weapons grade Pu weapon (WGPu, 4 kg), as adapted from S.Fetter, *et al.* (1990).[27] The table shows the number of neutrons or gamma rays arriving at a detector of area 1000 cm^2 at a distance of 5 m from the weapon of interest (labeled 'Detector'). The table also shows the ambient background neutrons and gamma rays for the same detector with background flux of 0.01 n/s-cm^2 and 0.3 g/s-cm^2 for neutron and gamma-ray background, respectively (labeled 'Bg').[28]

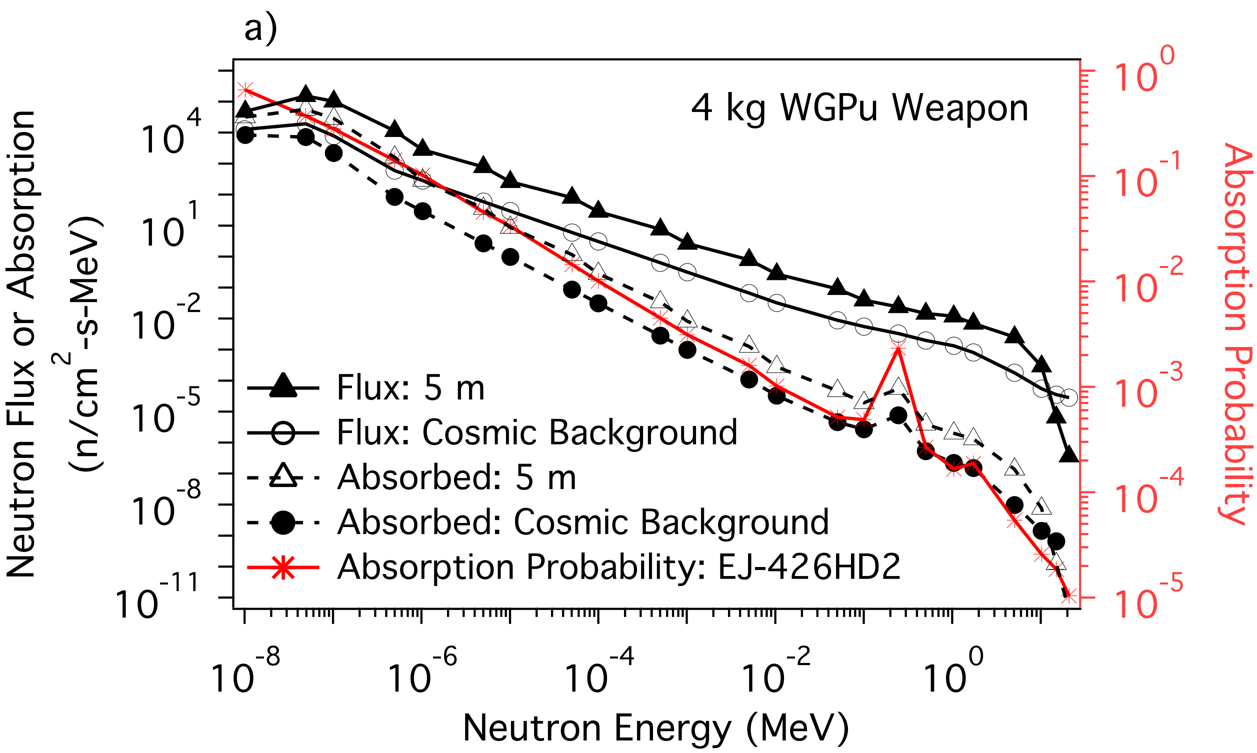
	Neutron (n/s)		Gamma-ray (g/s)	
	WGU	WGPu	WGU	WGPu
Surface	1400	400000	100000	60000
Detector	0.3	99.9	25.0	15.0
Bg	10	10	300	300

Simulation and Calculations of Detecting Nuclear Materials

The study undertaken herein investigates a hypothetical WGPu weapon. The model adapts that created by S.Fetter, *et al.* (1990)[29] and integrates a 4 kg shell of WGPu into a weapon form. The model considers a 1000 cm^2 area Zinc Sulfide (ZnS) -based detector 5 or 10 m from the WGPu weapon and includes intermediary air. The model is created in a Monte Carlo-based computational simulation to determine the flux of neutrons travelling onto the surface of the ZnS-based detector. The Monte Carlo simulation (MCNP6.1.1) computes scattering, absorption, and fission of source neutrons in the weapon itself as well as scattering and absorption in the intermediary air.[30] Information regarding neutron and gamma-ray emission rates is based on S.Fetter, *et al*. (1990)[31] and G.W. Philips, *et al*. (2005)[32].

The detector used in this study is a ^{6}Li:F loaded ZnS(Ag) plate. ZnS(Ag) is a scintillating material that, when loaded with ^{6}Li:F, becomes sensitive to neutrons due to neutron capture by the ^{6}Li and scintillation by energy deposition of the reaction particles. Previous studies have shown ZnS-based detectors to be potentially the most promising ^{3}He-free neutron detector technology, due to the relatively high neutron detection efficiency and potential for neutron-gamma discrimination capability.[33] Additionally, for this study the large detection areas that may be obtained and the commercial availability of ZnS-based detectors are important. Due to the limited world-wide supply of ^3He, ^3He-free neutron detectors or replacement technologies have become an important area of research, can be implemented into neutron detection systems, and are often considered the "gold-standard" for use in neutron detection.[34] For the purposes of calculating the absorption of neutrons into the detection medium, the material properties (including atomic density of ^6Li and mass density of the ZnS plate) of EJ-426HD2 by Eljen Technology are considered.[35]

The calculations are conducted in two parts: first, the number of neutrons that reach the detector face (flux) are determined as a function of neutron energy. The neutron flux spectra for both emitted neutrons from the WGPu at a distance of 5 m and from background are shown in Figure 3a. Second, the number of neutrons absorbed by the detection medium is calculated considering the absorption spectrum generated by the ^6Li isotopic density in a single plate of the ZnS-based detector and the flux spectra for emitted neutrons from WGPu and from background, also shown in Figure 3a. The absorption cross section is determined from ENDF libraries.[36] It is important to perform the calculations in terms of energy spectra, as absorption is not uniform across the energy range. The neutron spectra may then be summated to arrive at the total number of neutrons expected for flux and to be absorbed, as in Figure 3b. In Figure 3b a distance of 10 m and at the surface of the WGPu weapon is also considered. As expected from the calculations in Table 1, Figure 3b shows higher flux (and absorption) for a distance of 5 m compared to background, however, at 10 m the flux (and absorption) and background are similar.



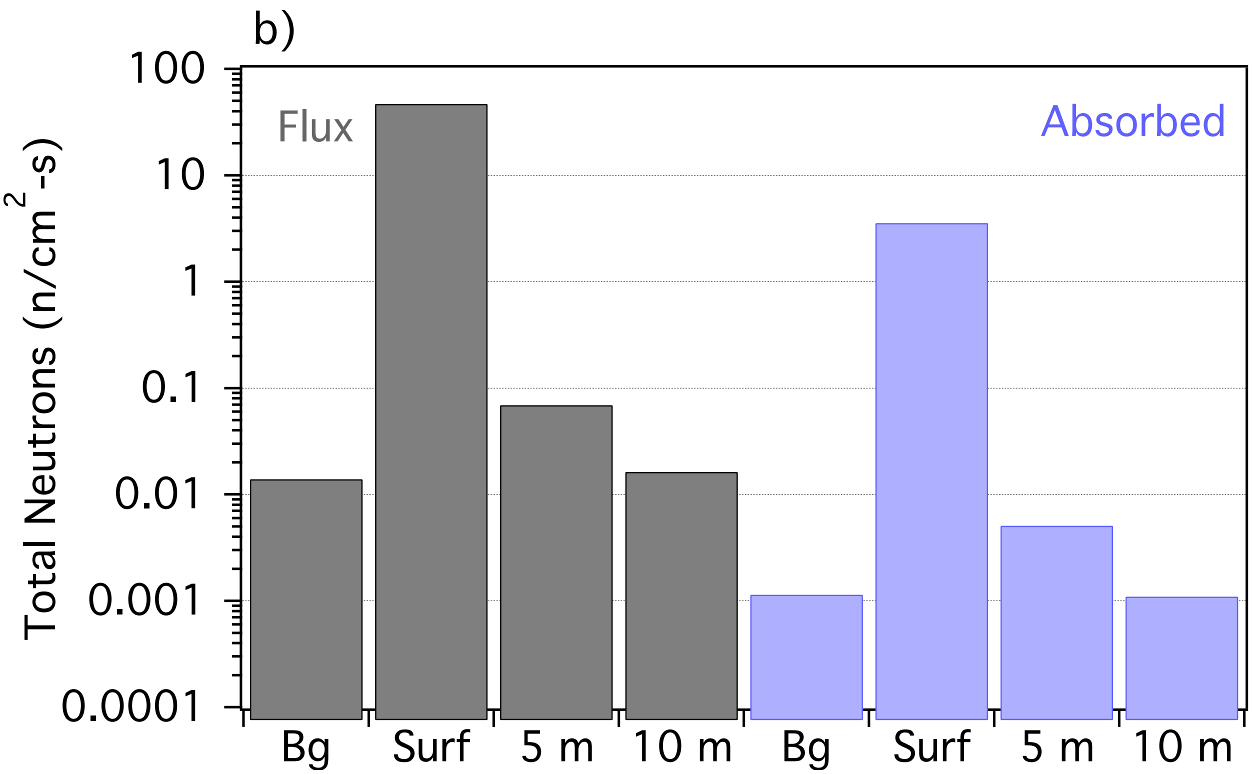
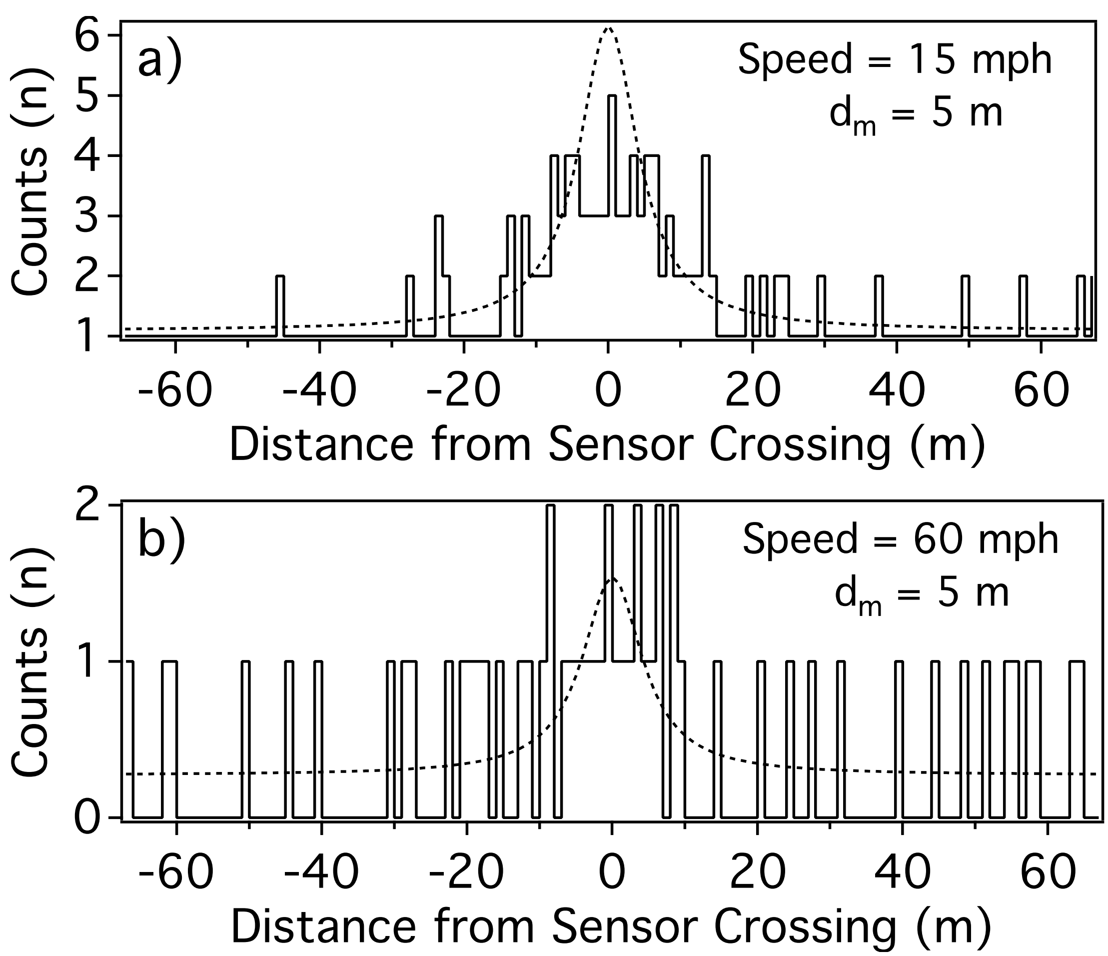


Figure 2: a) The neutron flux from WGPu at a detector distance of 5 m (solid line, black triangle markers) and due to background[37] (solid line, empty circle markers) is shown as a function of neutron energy. Neutron absorption into the detector as a function of neutron energy is also shown for neutrons from WGPu (dotted line, empty triangle markers) and background (dotted line, solid circle markers). On the right axis, the absorption probability for a 1 cm^2 portion of the ZnS-based (based on a single plate of EJ-426HD2 manufactured by Eljen Technology)[38] detector is shown (solid red line, star markers). **b)** Summation of the neutron spectra in a) yields the total number of neutrons incident onto the detector face (flux, in grey) on the left; while on the right the total number of neutrons absorbed into the detector (absorbed, in blue) is shown (background labeled as 'bg', source-detector separation distances of 5 and 10 m labeled as '5 m' and '10 m', respectively). In addition, the neutron flux and absorption is shown for the surface of the WGPu weapon (labeled 'Surf').

The calculations of flux and absorption only consider a single plate of the ZnS-based detector and an efficiency of converting an absorbed neutron into a detection event (count) as unity. Neutron-detector systems utilizing ZnS-based plates are likely to be formed of several plates with absorption-to-count efficiencies less than unity.[39] To address both these issues, it was assumed that the ZnS-based detector would meet an absolute neutron detection efficiency standard developed by R.T. Kouzes, *et al.* (2009)[40], which states that the detector would be able to generate 2.5 counts/second-nanogram from a ^{252}Cf source at a distance of 2 m from the detector. This standard was applied to the calculation results in Figure 3 by correcting the relative efficiency of the detector to meet to the standard, thereby forming a detector that considers multiple plates and a non-unity absorption-to-count efficiency.

Once the detector was corrected with the efficiency standard of R.T. Kouzes, *et al.* (2009)[41], it was scaled to an area of 1000 cm^2 and was studied in a traffic scenario to investigate and predict potential measurement results. The area of 1000 cm2 was selected because it is large enough to be effective in detecting WGPu at smaller distances (5 m, in this study), but is small enough to be feasible for commercial manufacturing and deployment. The traffic scenario examines the passage of a vehicle by a network detector, as in Figure 1. Figure 3a and b show sample temporal distributions of the predicted detector response and analytical response as a function of vehicle distance from crossing the detector. The responses are for total neutron counts (neutrons from WGPu and background). The analytical response is the probability of the detector producing counts from the passage of the vehicle by the detector, considering background neutrons. The predicted sample detector response discretizes the analytical response to whole counts and employs a random number generator to disperse counts according to the predicted detector response and the total number of counts within the full distance range displayed. In Figure 3c, the receiver-operator characteristic (ROC) curves show the probabilities of detecting WGPu *vs.* producing false alarms due to background neutrons. The ROC curves are given to exemplify the effects of vehicle speed and distance of closest approach to the detector, d_m. The distance of closest approach occurs when the vehicle is crossing nearest by the detector. Speeds were selected to approximate vehicles travelling on the highway (60 mph), using on/off ramps or roads (30 mph), and in heavy traffic or turning through an intersection (15 mph). The distance of closest approach of 5 m was selected as this distance roughly corresponds to the clearance height of a sign or bridge above a road, as in Figure 1. A distance of 10 m was selected as this distance roughly corresponds to a lane and a half of highway, including the shoulder, as in Figure 1 if the detector were placed on the ground at the base of the pole holding the traffic camera.



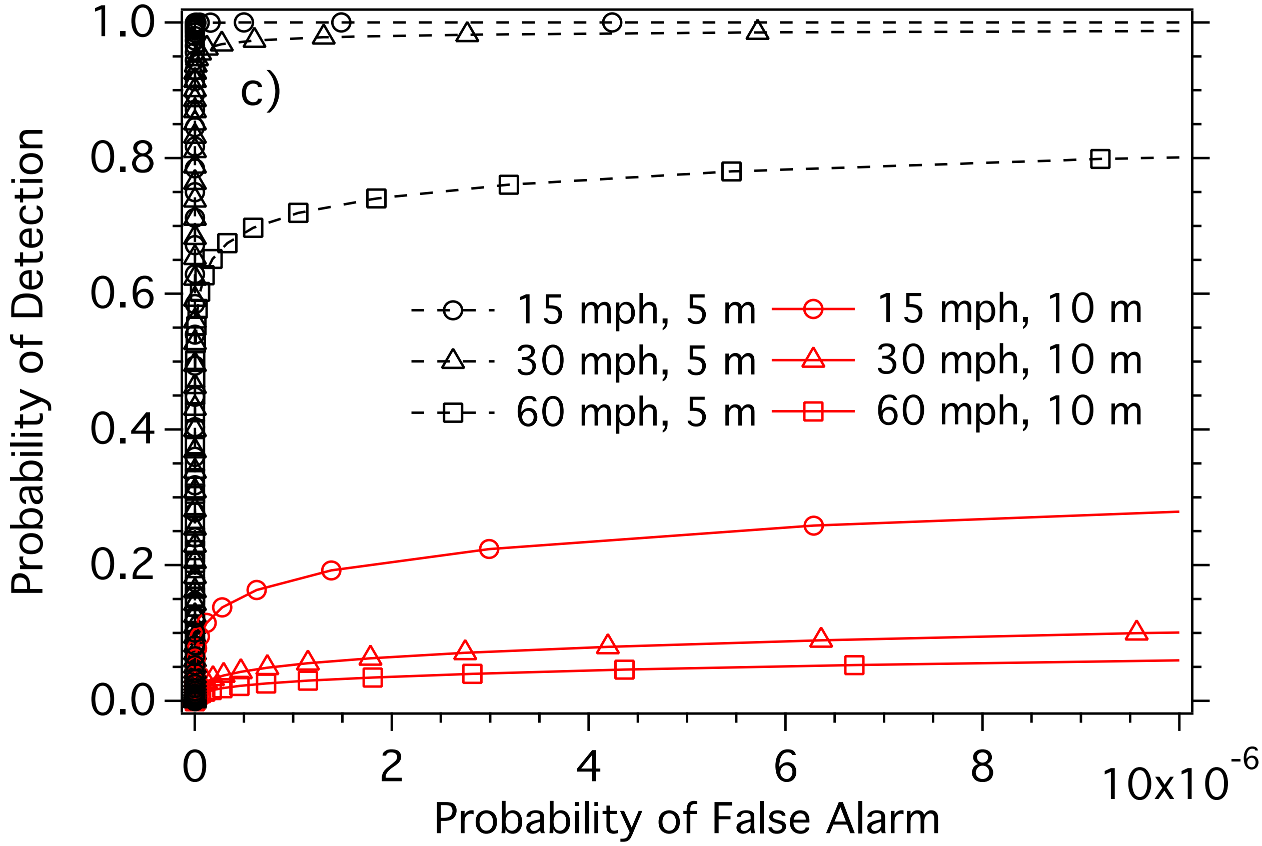


Figure 3: a) Displayed is the analytical response (dotted line) and predicted sample detector response (solid line) as a function of distance from crossing the detector for a scenario of a threat vehicle passing a network detector at minimum approach distance, d_m = 5 m, at a speed of 15 mph and b) 60 mph. c) The receiver operating characteristic (ROC) curves are given for d_m = 5 m (dotted black lines) and d_m = 10 m (solid red lines) for 15 (circle marker), 30 (triangle marker), and 60 (square marker) mph.

Figure 3a shows that the predictions for the passage of a vehicle containing the WGPu at a speed of 15 mph and d_m = 5 m would generate a clearly greater than background detector response (solid black line). Meanwhile, at a speed of 60 mph (Figure 3b), it becomes difficult to determine, by eye, the presence of the WGPu. However, according to the ROC curve in Figure 3c, the vehicle travelling at a speed of 60 mph and d_m = 5 m (dotted black line, black square markers) would have a fairly good probability to be detected, even for relatively small probabilities of false alarm. For d_m = 5 m, speeds less than 60 mph (i.e. 30 and 15 mph) have a much greater probability of detection for even smaller probabilities of false alarm. Unfortunately, at d_m = 10 m, the probability of detection is low compared to d_m = 5 m, regardless of vehicle speed. The conclusion drawn from Figure 3c is that vehicle speed is less important than distance of closest approach of vehicle to the detector, even for slower (15 mph) vehicle speed at larger distances. This conclusion is expected due to the non-linear (one over the distance squared) reduction in count-rate due to increasing distance as compared to the linear drop of count-rate due to reduction of counting time (represented by higher vehicle speed). Also, at d_m = 5 m detection probability is only marginally increased by slowing the vehicle lower than 30 mph. Finally, the detector is capable of detecting WGPu at d_m = 5 m up to highway speeds, with reasonably low probabilities of false alarm. While it is generally expected that distance between the vehicle and detector is more important than count time (vehicle speed), the use of distance and speed parameters that closely resemble what would likely be encountered in a detector deployment scenario illustrate the importance of this effect.

Threat Interdiction and Fallout Monitoring

Detection probability rates can be increased by combining measurements of several detectors along the line of travel of a vehicle. When a sufficient number of neutrons are recorded by a detector node within a time window, as in Figure 3a, and this number is greater than a predefined threshold, a detection alarm occurs, which may activate a traffic-monitoring device such as a camera or speed tracker. This information may be used to identify and predict the line of travel of the vehicle. Should the line of travel pass by additional detector nodes, the detector measurements can be combined. By aggregating several measurements of independent detector nodes, detection probability rates can be improved by increasing the total measurement time. Importantly, information from multiple traffic-monitoring devices can confirm that the measurements are taken of a particular vehicle (by photograph, for example) and that the vehicle's time of arrival at a subsequent detector position is reasonable considering the vehicle's speed (if measured). While not examined here, of notable importance is the stochastic nature of the network's effectiveness based on possible vehicle route and placement of detectors and traffic-monitoring devices. Hence, the deployment of a detector network would benefit from a thorough study of this stochastic effect on detector placement considering any particular city's roadway layout.

Interdicting a Threat Vehicle

In the traffic-based detector network concept, detection of threatening nuclear material is only a part of the equation to help prevent nuclear terrorism. Another major aspect is the interdiction of the threat-containing vehicle. By coupling the detector with a traffic-monitoring device, the network may obtain the vehicle's identity or appearance along with information such as location, direction of travel, and speed. This information on the threat vehicle can aid local law enforcement to search for and interdict the vehicle.

A benefit of any prototype effort would be the development of the operational concept for the use of any detection alarm and the subsequent development of a command and control system that supports that operational concept. The development of concepts of operation (CONOPs) focused on detection and interdiction of a threat vehicle would require forethought into how a network detection concept may be integrated with existing communication, assessment, and response assets. Once a concept for the interdiction response is established and practiced, such a command and control system would link the processed traffic information to a dispatch system that can communicate to police in the field for interdiction.

Detector Network for Fallout Measurement

In the unfortunate circumstance that a nuclear device detonates or an accident occurs, radioactive fallout would likely be dispersed. Emergency-response personnel and resources would be distributed around the blast zone to help evacuate and triage victims. Many emergency-response personnel units carry radiation detection equipment, such as personal radiation monitors, or pagers.[42] These radiation monitors can assess dose rate for the person wearing the device once they have already entered the fallout zone. Depending on the dose rate, the emergency responders may have limited time to conduct activities, or may have to evacuate themselves from the area. Evacuation may be tricky, due to the quickly evolving nature of fallout, which is dependent on local weather conditions. Generally, there is not an efficient method of ascertaining dose rate as a function of location and time other than the use of radiation monitors worn by emergency responders (with some exceptions, such as the deployment of radiation monitors at firehouses in the District of Columbia).[43] This method of assessing dose rates may place response personnel at risk of excessive radiation exposure. Time and resources may potentially be wasted if, for example, repeated redeployment is necessitated by unpredictably changing dose rates.

Given that a communications network would need to support the transfer of nodal information, the radiation detector network could provide information of fallout dose rates as a function of location and in real-time. This information may be relayed from the decision makers at the central node. While some detector nodes would be destroyed in the blast, there would still be an array of nodes outside the blast zone, depending on the size of the blast. These surviving nodes can continue operating with backup batteries in the case of loss of electrical power. However, the damage to electronics and communications due to electromagnetic pulse effects would also have to be considered and studied. There would also need to be contingencies for the event that the local central node is damaged or destroyed, such as the implementation of a remote central node.

Calculations of mRem/hr dose to count rate for a ^{137}Cs (662 keV) gamma ray suggest that for an unshielded ZnS-based detector the effective range of dose measurement is between 0.1 to 1000 mRem/hr. below 0.1 mRem/hr, and the gamma-ray flux at the detector is not great enough to determine the certain existence of radioactive fallout. Above 1000 mRem/hr, the detector becomes overwhelmed by the gamma-ray flux and detector dead-time and pulse pileup begins to affect the detector performance,[44] however it may still be possible to correlate detector measurements to dose above 1000 mRem/hr. The calculations do not consider the use of an electronic-based gamma-ray discrimination algorithm, which may be shut off during measurements of gamma rays. Assuming that the information from the detector network is transmitted to and processed by a central node, this information can then be forwarded to decision makers directing emergency response efforts. The range of dose that the ZnS-based detector can measure places its utility within a "hot zone" area where lifesaving activities can be conducted under close monitoring of accumulated dose of response personnel.[45] While the assessment of fallout and dose in urban environments after a nuclear blast can be predicted with computational models, the modeling results may not be immediately available. Also, dose information from the detector network provides actual data points that can be appropriated by models and compared with model results. The ability of the detector network to provide dose-rate information may be important in deciding if, when, and where emergency response personnel and resources may be deployed. The detector network can provide information of potential evacuation routes, and can track the evolution of dose from fallout.

The exact nature and evolution of the fallout would be dependent on detonation location. The detonation target and actual location where detonation takes place may not be the same. It is assumed that the likely target for the blast in many cities would be the city center. However, the actual location of the blast would be dependent on factors like size of the weapon, routes taken by the vehicles, and possible premature detonation. Assessments of likely target locations would be beneficial in determining deployment locations and densities of network nodes to prevent the weapon's detonation at the target or to redirect the detonation location to a less devastating area. Also, assessment of likely detonation locations could inform models to analyze likely routes to those locations. Modeling of likely detonation locations (and effective blast radius) would be beneficial in determining the efficacy of the network in fallout monitoring and detector-node placement. However, it is noted here that optimal placement of nodes for the objective of fallout monitoring may not be at the same locations as for the objective of threat detection (identification of vehicles on the way to a likely blast location).

Cost of a Prototype Network

The cost of deploying a prototype detector network for ground traffic is roughly estimated, producing a ROM (rough-order-of-magnitude) cost. For this estimate, the city of Washington D.C. was used as an example with detectors installed at 140 traffic-monitoring device locations, particularly all red light cameras (50 estimated)[46] and all speed traps (90 estimated)[47]. The anticipated cost per installation is $25,000, while the cost per detector is assumed to be $200,000 for Li-based scintillating neutron detector systems.[48] The estimated ROM expenditure for deployment of a detector network for ground traffic is expected to be approximately $32 million dollars for the city of Washington D.C. It is possible that economies of scale can reduce the cost of the detector systems, but that is not assumed. This cost also does not consider the likely significant expenditures required for communications network installation, monitoring, and maintenance, nor does it consider the cost to ensure network security standards, which are necessary to prevent hacking. The security of the communications network would likely need to be more robust and resilient to hacking than those implemented for traffic cameras.

In order to provide useful information on real false alarm rates, as well as to catalyze the development of operational responses, the system must be maintained and operated. The operational costs of the network, and of repairing and replacing parts of the network, are not estimated in detail here. Still, a very rough estimate helps bound these costs. Older, film-based, red light cameras in 2001 had operational costs of approximately $60,000 per year per location.[49] Since this requires regular access to the camera for film change, processing, etc., the purely electronic information from the nuclear detectors is assumed to be cheaper to access, but at the same time, the cost of spare parts and maintenance might be more. Using that number, though, would indicate about $8.4 million per year in operational costs, or approximately the acquisition cost for 4 years of operation (for Li-based detectors). This cost does not consider the operational cost of law enforcement interdiction activities, reach-back support, or cost to develop, test, and train on CONOPs.

The deployment of detectors onto mobile platforms, such as law enforcement vehicles, may add deterrence value, as discussed in Section VII. If such an approach is considered, the cost of installation of the detector is considered in this study to be negligible compared to the cost of the detector itself. Thus, the cost of deployment of the studied detectors onto law enforcement vehicles would be approximately $200,000 per vehicle,[50] or the cost of the detector. For the same $31.5 million that could be used to deploy a detector network at traffic-monitoring systems (140 locations) in Washington D.C., approximately 160 law enforcement vehicles could be equipped with the same technology. It should be noted that additional studies should be carried out to assess the technical efficacy of such a method of detection and deployment. Again, this cost does not consider the operational cost of law enforcement interdiction activities, training, or reach-back support.

Determining the affordability of such a detection network is challenging due to factors such as actual damage done by a nuclear detonation (i.e. if the detonation was a full or only partial yield), location of the blast, amount of destruction and remediation of damage and fallout required, and the full cost of the network itself. One comparative scenario is the terrorist attacks on the World Trade Center in New York City on September 11th 2001. The total economic impact to New York City due to the 9/11 attacks is approximated as at least 83 billion dollars with about $22 billion due to physical destruction and $9 billion dollars of that accounted by human potential loss.[51] Assuming that the devastation caused by a nuclear blast in a city of similar density would result in at least an order of magnitude larger area of destruction and lives lost, the economic impact could result in the magnitude of hundreds of billions to trillions of dollars in impact from physical damage and human potential loss alone. It would seem such a calculation easily suggests the affordability of deploying a detection network, which is estimated to be less than a hundred million dollars. However, there are some probabilistic points regarding the cost equivalent of the consequences of a possible attack, including: a) an actual attack is carried out, b) the weapon is Pu-based (which, also has cost implications for development and deployment of the detector network), c) the weapon is detected by the network, and d) interdiction occurs without detonation or is detonated off-target.

Potential Benefits of the Network

The described radiation detection network has several advantages not necessarily true of other detection networks. First, the detectors may be coupled with existing traffic-monitoring devices. By doing so, costs of providing power can be reduced as they may be shared with the existing traffic-monitoring device. The traffic-monitoring device can also provide supplementary information (photograph, for example) of the threat vehicle, which can be fused with detector measurements to verify measurements made by additional detector nodes and thus increase the probability of detection. The same supplementary information can be used for identifying the threat vehicle to aid in search and interdiction of the vehicle. It should be noted that there exist uncertainties in a given threat vehicle route and difficulties in detecting threat material at longer distances and shorter measurement times (faster vehicle speeds) with greater difficulty for increasing distance. While there are technical challenges in the fusion of data, such as temporally aligning detector data with traffic-monitoring information, such a concept has been previously proposed, for example, in Operation Sentinel.[52] Second, the detector network has dual purposes: to help prevent an attack with a nuclear device by detecting and aiding the interdiction of threat materials, and to assist emergency response in the event of a nuclear attack by collecting dose-rate information as a function of location and time. Decision makers can utilize the dose-rate information to aid the determination of efficient deployment of emergency personnel and resources.

Third, the concept of the detector network can first be utilized in the development of operational CONOPs and in understanding and navigating policy implications. However, given the fairly advanced state of work of neutron detectors and their commercial availability, limitations of deploying such a detector network are beginning to shift from detector capabilities to operational considerations.[53] A limited prototype network that couples with traffic-monitoring systems could be set up to assess the efficacy of individual detectors and the whole network, which can be iteratively applied to improve the design and data analysis of the detectors, the network, the data they produce, and the method and means of interdiction. Importantly, the operational aspects of the use of the detection network can be established, studied, and grounded in testing experiences. They may also be integrated with other modalities of detection. As noted above, such operational aspects include the cooperation of various local, state, and federal resources to interdict a threat vehicle, or experimenting with various detector deployment locations or configurations to enhance detection probability and speedy interdiction. Development of CONOPs and exercises would provide valuable knowledge that may improve the efficiency and effectiveness of command and control systems, and threat response. The lessons learned from deploying, operating, and improving such a limited prototype network would likely provide valuable insights for other detector modalities or other types of networked threat search and monitoring. The development of CONOPs, however, would likely need additional analyses to identify the most likely targets of an attack and effective sensor-deployment locations and density to interdict approaches to these potential target epicenters.

Potential Drawbacks of the Network

The radiation detection network explored in this work also has some drawbacks. Unpredictability of node locations or node density may help to deter nefarious activities by adding an unknowable aspect to an adversary's plan. However, in this concept, unlike some radiation detector networks that are based on moving, unlocatable, or otherwise unpredictable node locations or density, the detectors of the network in this work are fixed in location. Not only are the locations of the detectors fixed, but also they are knowable since the detectors are deployed in the vicinity of a traffic-monitoring device.

To overcome the important issue of unpredictability and deterrence of the network, moving detector nodes should be also explored, which would be an addition to and would work in cooperation with the network. Such moving nodes may include detectors installed on vehicles. Given the size of the detector studied (1000 cm^2), mobile detector systems could be deployed on law enforcement vehicles, for example, that monitor nearby or passing vehicles for the presence of WGPu. In the occurrence of a detection alarm, the law enforcement vehicle carrying the detector could attempt to follow the potential threat vehicle to accumulate longer measurement times, lowering the probability of false alarm. The advantages of identification of the threat vehicle for aiding interdiction, as carried out by the coupling with traffic-monitoring systems, would be assumed by the law enforcement officer. Mobile platforms could increase deterrence value by adding uncertainty to the prospect of being discovered, as the presence of law-enforcement vehicles or which ones are equipped with a detection system cannot be preplanned by an adversary. Another method to increase deterrence value is the deployment of dummy detectors, or equipment that mimics the appearance of a functional detector system. These dummy detectors would add deterrence value by varying the adversary's calculus of planning to avoid detection. Adversaries may reconsider executing an attack, given an encounter with a much larger and denser network of potentially functional detectors. Even with the knowledge that some detectors are dummies, not knowing which ones are functional would add some deterrence value to the detection network concept.

Second, for the passive detectors investigated in this study, the use of sufficient amounts of appropriate shielding can attenuate neutrons exiting the source, hiding the nuclear material from the detector. Such shielding certainly complicates the plan to transport a weapon, which would have some indeterminate deterrent effect, but it is feasible. In the case of shielding, parameters of network node density, detector size, vehicle speed, or source-detector distance may be of little importance. In part, it is because of this shielding problem that active interrogation detector systems are a large and essential part of on-going research in the field of nuclear-materials detection.[54]

Third, the detection probability of a detector within the network was analyzed for only WGPu due to the relatively small number of neutrons emitted from uranium. It is estimated that the detection of uranium would not be feasible in the network-detection concept for ground-based traffic. This leaves a sizable gap in nuclear materials detection capability.

Comparison with Other Alternatives

There are alternatives to the concept explored in this paper for threat-source search and post-blast fallout and radiation monitoring. Some of these alternatives include the deployment of personal radiation detectors (PRDs) onto law enforcement and first responder vehicles and personnel, or the use of radiation sensors on unmanned aerial vehicles (UAVs). Both of these alternative concepts may be utilized in threat-source search and post-blast radiation and fallout monitoring. Here, we will briefly examine some of the costs, benefits, and drawbacks of these alternatives. Another strategy to source-search is the scanning of vehicles and cargo at border crossings, ports, and airports. This strategy relies on a wall-like defense against the smuggling of nuclear materials into the country. This strategy will also be briefly discussed.

Personal radiation detectors (PRDs) are typically belt-worn or handheld pager-sized detectors with electronics that allow ease of use and customized setting of exposure alarm, all at a price usually below $10,000 per unit.[55] They can be worn by law enforcement officers and first responders, and the concept of implementing them as part of the strategy to detect nuclear and radiological materials has already been undertaken as part of "Securing the Cities" program of DHS.[56]

A first approximation of the number of PRDs that would likely be worn by law enforcement officers in D.C., for example, would be 2800, or the number of body cameras deployed.[57] The officers who would wear body cameras are also likely the officers that would provide operational impact to nuclear materials search and radiation monitoring by wearing PRDs. Considering a lower-end price of $2,000 per PRD would bring the total equipment cost to $5.6 million, or about 17.5% of the equipment cost of the traffic detector network. The equipment cost does not consider required training, reach-back support, or cost to respond to detection-alert scenarios. A benefit of these detectors is the ability to distribute them widely, due to the low price point per unit. Another benefit is that the PRD can alert officers, who already have some authority to stop attacks and maintain public safety, to localized elevated rates of radiation. Yet another benefit is the relatively random distribution of law-enforcement officers and their PRDs about a city. While an adversary may likely try to avoid close proximity to an officer, this cannot be guaranteed, thereby adding to deterrence. A drawback of PRDs is their significantly smaller volume of detection (typically no larger than a few cm^2), which requires the detector to be in much closer proximity to the radiation source or to have much longer dwell time than the detector analyzed for the traffic network concept.

Another alternative to source-search and post-blast fallout and radiation monitoring is the use of radiation detectors on unmanned aerial vehicles (UAVs). The technology of compact UAVs has advanced significantly in the past years to the point where UAVs equipped with radiation detection capabilities are commercially available. While many of these systems are designed for gamma-ray detection, a custom setup could be built, using a detector panel from the traffic detector network concept fixed onto a UAV. A 1000 cm^2 ZnS:LiF detector would weigh approximately 3 lbs.[58] Even with required electronics and power supply, the weight of the detection system would be within the payload capacity of current commercially available UAVs (20-25 lbs.), such as the DJI Agras MG-1.[59]

If we use the DJI Agras MG-1 as an example, the cost per UAV is approximately $15,000. With the previously calculated cost per detector at $200,000,[60] the equipment cost per detector-equipped UAV comes to $215,000. This does not consider the cost of required communications systems, reach-back support, usage training, or any modifications to extend flight time or range. If we consider the number of UAV detector systems to equal the number of traffic-based detector systems (140), the total equipment cost of this alternative is $30.1 million, which is approximately equal to that of the traffic-based detector network concept cost.

A benefit of UAV-based detection concept is the control, within the limits of the physical range and battery life of the UAV, of where, when, and for how long the detectors dwell at a location. Another benefit is the ability to follow objects of interest (within the speed limitation of the UAV) or bring multiple detectors to a point of interest for better detection capability. In post-blast fallout and radiation monitoring, UAVs have an advantage of potentially being deployed after the blast, thereby preserving them from destruction. They also have the advantage of being mobile to assess radiation levels along evacuation routes or to develop understanding of the nature of the fallout due to weather conditions. Drawbacks, however, can be operationally substantial with limitations on the operation time and range of a given UAV. Additionally, while the CONOPs of a UAV-based system would need to be fleshed out, perpetual deployment would seem unlikely. The UAVs would instead likely be deployed during major events (e.g. sporting events) or in response to information that threat material was in the area or that an attack was imminent. This contrasts with the relatively perpetual operation of the detectors in the traffic-based concept. However, when UAVs are deployed in source-search, deterrence value is added due to the highly mobile nature of the UAVs.

An alternative to placing detectors in urban environments is the strategy of scanning vehicles and cargo coming into the U.S. through ports, airports, and border crossings, which is already carried out by DNDO in cooperation with other federal agencies.[61] As this line of defense is a fundamental part of preventing nuclear smuggling into the U.S., it should strive continuously for improvement. Covert field tests of the integrity of this line of defense were carried out by the CBP and showed varied levels of success. A Government Accountability Office report recommended a risk-assessment study should be conducted to prioritize the makeup and deployment of resources.[62] Additionally, an unavoidable deficiency with this defense includes susceptibility to circumvention by going around or avoiding known checkpoints.[63] While there may be some deficiencies with this particular line of defense, it is part of a multi-layered defense strategy of the GNDA that also includes inland inspection of trucking cargo at weigh stations.[64] The concept of a traffic-based detector network explored in this article is not intended as a replacement for existing defenses but may be integrated as yet another layer of this multi-layered strategy. In the event that port, airport, or border detection fails, the traffic-based detector network provides scanning opportunities at likely targets of substantial devastation – in the cities.

A strong defense against a nuclear attack would likely rely on the combination of detection concepts. The benefits of the described concepts may overlap to overcome drawbacks. In any case, CONOPs of the system would need to be developed, which ideally emphasize the key benefits of each concept, such as the pervasiveness of PRDs, mobility of UAVs, and operational perpetuality of traffic-based detectors. The radiation detection concepts discussed here could also become a part of the multi-layered defense strategy that includes the GTRI, which secures nuclear materials and processes at facilities,[65] and the GNDA, which seeks to reduce the risk of nuclear attacks by inspection of cargo, vehicles, and persons travelling into the U.S. through ports, airports, or border crossings.[66]

Conclusion

The threat of nuclear terrorism to U.S. cities is serious and the consequences of such an attack would be significant. The potential consequences of a nuclear detonation in a city include loss of life, widespread destruction, and a substantial negative impact on the economy. The U.S. government has responded by establishing and supporting agencies, such as the NNSA and the DNDO, with the purpose of reducing the threat of nuclear terrorism. These agencies advance programs that reduce and secure nuclear materials and strengthen inspection regimes at home and abroad. These agencies and others (such as the Defense Threat Reduction Agency and the Defense Advanced Research Projects Agency) along with their parent departments (DOE, DHS, and DOD) have made appreciable investments into radiation-detection technologies and research to help track, scan, and search for nuclear materials and weapons.

This article reviews and investigates one such concept in terms of technical feasibility – the use of radiation detectors in a networked configuration and deployed next to roads for ground-based traffic monitoring with the possibility of deployment onto mobile platforms. This investigation lays out the basis of the concept, however analysis of the integration of such a network with command and control systems, the details of the operational process, and assessing the likely epicenter targets, vehicle travel routes, and optimal placement of detectors is also required for any successful development of even a prototype test network.

Detectors within the network measure the presence of neutron radiation from nuclear materials and weapons that may be contained in passing vehicles. The detectors would be deployed at existing traffic-monitoring system locations (stop light or red light cameras, for instance) such that when a detection alarm occurs, the traffic-monitoring device can be activated to identify the threat vehicle. While not explicitly analyzed here, additional detector measurements and traffic-monitoring device information may be taken along a vehicle's line of travel to verify vehicle identity and increase the certainty of detection. Other aspects of the concept not explored here but which would require further investigation are how measurements from the detector and information from the traffic-monitoring device would be communicated to a central node, how that information is fused and interpreted, and the decision-making process of vehicle interdiction. If interdiction were carried out, information from the traffic-monitoring device(s) would aid the search for the threat vehicle. In a scenario in which a nuclear weapon detonation or nuclear accident has already occurred, the detector network could provide location and time-dependent measurements of radioactive fallout. Measurements of dose rate can be fed to the central node, interpreted, and utilized to aid in the decision-making for the deployment of emergency-response personnel and resources. Here again, transfer and interpretation of information, and decision-making are aspects that would require in-depth investigation.

The study finds that the detection network concept appears to be feasible for neutron detection of weapons grade plutonium, but not uranium, up to highway speeds (60 mph) at a minimum detector distance of 5 m from the plutonium, which is plausible. The neutron emission from weapons-grade uranium, compared to background, was estimated to be too low to be detected by a detector in the concept of ground-based traffic. At a minimum detector distance of 10 m from the plutonium, the detector is capable of detecting the presence of plutonium but at relatively low probabilities of detection. It was shown that decreasing the minimum detector distance from the plutonium is more important than the vehicle speed for the speeds studied (15, 30, 60 mph).

Opportunities for Future Work

Future work analyzing the detector network for ground-based traffic concept should include the evaluation of other neutron (other than ZnS-based) detector types and detector sizes to optimize the potential efficacy of the network and/or minimize costs, and should examine how to fuse the detector measurement and traffic-monitoring system information in order to identify a threat vehicle. Further studies should explore the effect of aggregating multiple detector measurements and investigate the concept of moving detector nodes to enhance the detection network concept's deterrence value. Additional future work should also be carried out to understand the effects of shielding on detection capabilities, traffic-flow modeling for optimal detector placement, and likely epicenter targets and blast radii for understanding the capability of the network for fallout monitoring. This additional future work would reveal limitations of the concept that may affect its overall feasibility or point to aspects of the concept which may be strengthened. Finally, future work should also be carried out to explore the effectiveness of the combination of multiple detection modalities.

Importantly though, the concept explored here is not expected to be only solution to the challenging issue of nuclear terrorism. Instead, further investigation should be carried out to explore how this traffic-based detector network concept and potential alternative technologies and concepts can be appropriately mixed to strengthen the layered defense homeland security strategy to prevent nuclear terrorism.

About the Author

Edward Cazalas is an Assistant Professor of the Nuclear Engineering program within the Civil and Environmental Engineering Department at the University of Utah. Edward was also a former postdoctoral researcher at the Air Force Institute of Technology and a former Stanton Nuclear Security Postdoctoral Fellow at RAND Corporation where he performed the origination of this work. Edward holds a Ph.D. in Nuclear Engineering from the Pennsylvania State University. He has research interests in developing radiation-detection science and technologies and advancing the understanding of dosimetry for nuclear and radiological exposure events and processes. He may be reached at edward.cazalas@utah.edu.

Notes

1 C. Meade, & R.C.Molander, *Considering the Effects of a Catastrophic Terrorist Attack*, Santa Monica, CA: RAND Corporation (2006), Available at: http://www.rand.org/pubs/technical_reports/TR391.html.

2 Bunn, et al., *Preventing Nuclear Terrorism: Continuous Improvement or Dangerous Decline?* Cambridge, MA: Report for Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School (2016).

3 National Nuclear Security Administration, Prevent, Counter, and Respond – A Strategic Plan to Reduce Global Nuclear Threats (2017) https://www.energy.gov/sites/prod/files/2017/11/f46/fy18npcr_final_november_2017%5B1%5D_0.pdf.

4 K. Guthe, "The Global Nuclear Detection Architecture and the Deterrence of Nuclear Terrorism," *Comparative Strategy* **33,** 424–450 (2014).

5 W.Stern and E. Baldini, "Global Threat Reduction Initiative Efforts to Prevent Radiological Terrorism, " *Federation of American Scientists: Public Interest Reports* **44** (2013).

6 L.Cuéllar, *et al.,* "Probabilistic Effectiveness Methodology: A Holistic Approach on Risk Assessment of Nuclear Smuggling, " *IEEE International Conference on Technologies for Homeland Security,* 325–331 (2011).

7 S. Fetter *et al.,* "Detecting Nuclear Warheads," *Science and Global Security* **1,** 225–253 (1990).

8 A.D. Lavietes *et al.,* "Technical Review of the Domestic Nuclear Detection Office Transformational and Applied Research Directorate's Research and Development Program, " *IEEE Access* **1 ,** 661–690 (2013).

9 T. Kijewski-Correa *et al.,* "Real-time Plume Detection in Urban Zones Using Networked Sensing Data," *Proceedings of Chem-Bio Defense Physical Science and Technology Conference* (2008).

10 R.W. Nelson, "Concept of Operations for CBRN Wireless Sensor Networks," (Naval Postgraduate School, 2012).

11 B.R. Buddemeier et al., *National Capital Region Key Response Planning Factors for the Aftermath of Nuclear Terrorism,* Lawrence Livermore National Laboratory, LLNL-TR-512111 (2011).

12 International Atomic Energy Agency, *Manual for First Responders to a Radiological Energency,* (2006), available at: https://www-pub.iaea.org/books/IAEABooks/7606/Manual-for-First-Responders-to-a-Radiological-Emergency.

13 C. Meade and R.C. Molander, *Considering the Effects of a Catastrophic Terrorist Attack,* (Santa Monica, CA: RAND Corporation, 2006), Available at: http://www.rand.org/pubs/technical_reports/TR391.html.; U.S. Department of Homeland Security, *Quadrennial Homeland Security Review,* (2014) available at: https://www.dhs.gov/quadrennial-homeland-security-review.

14 A. Liu, Simulation and Implementation of Distributed Sensor Network for Radiation Detection, Master's Thesis, California Institute of Technology, Pasadena, CA, 2010.

15 Defense Advanced Research Projects Agency, DARPA SIGMA (2016), available at: http://www.darpa.mil/program/sigma.

16 Department of Homeland Security, FY 2016 Congressional Budget Justification, (2016), available at: https://www.dhs.gov/publication/congressional-budget-justification-fy-2016.

17 T. Kijewski-Correa, *et al.,* "Real-time Plume Detection in Urban Zones Using Networked Sensing Data," *Proceedings of Chem-Bio Defense Physical Science and Technology Conference* (2008); S.M. Brennan, A.M Mielke, and D.C. Torney, "Radioactive Source Detection by Sensor Networks, " *IEEE Transactions on Nuclear Science* **52,** 813–819 (2005).

18 R.J. Nemzek *et al*., "Distributed Sensor Networks for Detection of Mobile Radioactive Sources," *IEEE Transactions on Nuclear Science* **51,** 1693–1700 (2004); J.C. Chin *et al.,* "Identification of Low-level Point

Radioactive Sources Using a Sensor Network," *ACM Transactions on Sensor Networks* **7,** 21:1–21:35 (2010); D.S.Hochbaum and B.Fishbain, "Nuclear Threat Detection with Mobile Distributed Sensor Networks," *Annals of Operations Research* **187,** 45–63 (2011); H.Wan, T. Zhang and Y.Zhu, "Detection and Localization of Hidden Radioactive Sources with Spatial Statistical Methods, " *Annals of Operations Research* **192,** 87–104 (2012); K. Grunden, G. Guerra and W. Leonard, *Ubiquitous (CB)RN(E) Sensor Networks: Analysis and Framework Study,* TASC INC. (2014); L.M. Wein and M.P. Atkinson, "The Last Line of Defense: Designing Radiation Detection-Interdiction Systems to Protect Cities from a Nuclear Terrorist Attack," *IEEE Transactions on Nuclear Science* **54,** 654–669 (2007).

19 Y. Yang *et al*., "A Network Protocol Stack Based Radiation Sensor Network for Emergency System," *International Journal of Computer Science and Network Security* **8,** 312–318 (2008); F. Ding et al., "A GPS-Enabled Wireless Sensor Network for Monitoring Radioactive Materials," *Sensors and Actuators A: Physical* **155,** 210–215 (2009).

20 R.W. Nelson, "Concept of Operations for CBRN Wireless Sensor Networks," (Naval Postgraduate School, 2012); D. Srikrishna, A.N Chari and T.Tisch, "Deterence of Nuclear Terrorism with Mobile Radiation Detectors," *Nonproliferation Review* **12,** 573–614 (2005); S. Johnson, "Stopping Nuclear Terrorism is a Game of Odds, Not Certainty," *Wired* (2015).

21 D. Srikrishna, A.N Chari and T. Tisch, "Deterence of Nuclear Terrorism with Mobile Radiation Detectors."

22 A. Mauroni, " Nuclear Terrorism: Are We Prepared?" *Homeland Security Affairs* 8, Article 9 (June 2012). https://www.hsaj.org/articles/222.

23 R.Harney, "Inaccurate Prediction of Nuclear Weapon Effects and Possible Adverse Influences on Nuclear Terrorism Preparedness," *Homeland Security Affairs* 5, Article 3 (September 2009). https://www.hsaj.org/articles/97 .

24 Government Accountability Office, *Neutron Detectors: Alternatives to Using Helium-3,* GAO-11-753 (2011).

25 G.F. Knoll, *Radiation Detection and Measurement,* 3rd Ed. (Wiley, 2011).

26 G.W. Philips, D.J. Nagel and T. Coffey, *A Primer on the Detection of Nuclear and Radiological Weapons*. Defense Technology Paper 13 (2005); G.E. McMath, G.W. McKinney and T. Wilcox, *MCNP6 Cosmic & Terrestrial Background Particle Fluxes – Release 4,* Los Alamos National Laboratory, LA-UR-14-24445 (2015).

27 S. Fetter *et al.,* "Detecting Nuclear Warheads," *Science and Global Security* **1,** 225–253 (1990).

28 G.W. Philips, D.Nagel, and T.Coffey, *A Primer on the Detection of Nuclear and Radiological Weapons*, Defense Technology Paper 13 (2005); G.E. McMath, G.W. McKinney and T. Wilcox, *MCNP6 Cosmic & Terrestrial Background Particle Fluxes – Release 4*. Los Alamos National Laboratory, LA-UR-14-24445 (2015).; S.Fetter *et al.,* "Detecting Nuclear Warheads."

29 S. Fetter *et al.* "Detecting Nuclear Warheads."

30 T. Goorley, *MCNP6.1.1-Beta Release Notes*, (2014).

31 S. Fetter. *et al.,* "Detecting Nuclear Warheads."

32 G.W. Philips, D. Nagel and T. Coffey, *A Primer on the Detection of Nuclear and Radiological Weapons*.

33 J.H. Ely *et al., Final Technical Report for the Neutron Detection without Helium-3 Project,* (2013), Pacific Northwest National Laboratory, PNNL-23011 (2013).

34 S. Fetter *et al.,* "Detecting Nuclear Warheads."

35 *Thermal Neutron Detector EJ-426,* Eljen Technology (2016), available at: http://www.eljentechnology.com/index.php/products/neutron-detectors/ej-426.

36 Brookhaven National Laboratory - *Evaluated Nuclear Data File (ENDF/B-VII.1),* National Nuclear Data Center (2011), available at: https://www.nndc.bnl.gov/exfor/endf00.jsp.

37 S. Fetter *et al.,* "Detecting Nuclear Warheads."

38 *Thermal Neutron Detector EJ-426*, Eljen Technology (2016), available at: http://www.eljentechnology.com/index.php/products/neutron-detectors/ej-426.

39 J.H. Ely *et al., Final Technical Report for the Neutron Detection without Helium-3 Project*.

40 R.T. Kouzes *et al*., *Neutron Detector Gamma Insensitivity Criteria,* Pacific Northwest National Laboratory, PNNL-18903 (2009).

41 Ibid.

42 B.R. Buddemeier *et al*., *National Capital Region Key Response Planning Factors for the Aftermath of Nuclear Terrorism,* Lawrence Livermore National Laboratory, LLNL-TR-512111 (2011).

43 Ibid.

44 J.H. Ely *et al., Final Technical Report for the Neutron Detection without Helium-3 Project*; J.B. Mosset *et al.,* "Evaluation of Two Thermal Neutron Detection Units Consisting of ZnS/6LiF Scintillating Layers with Embedded WLS Fibers Read Out with a SiPM," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **764,** 299–304 (2014).

45 B.R. Buddemeier et al., *National Capital Region Key Response Planning Factors for the Aftermath of Nuclear Terrorism*.

46 *Red-Light Camera Locations,* Metropolitan Police Department (2016), available at: https://mpdc.dc.gov/publication/automated-traffic-enforcement-camera-locations.

47 *Speed Camera Locations,* Metropolitan Police Department (2016), available at: https://mpdc.dc.gov/publication/automated-traffic-enforcement-camera-locations.

48 Centers for Disease Control and Prevention, *Injury Prevention & Control: Motor Vehicle Safety – Invention Fact Sheets for Automated Enforcement,* (2015), available at: http://www.cdc.gov/motorvehiclesafety/calculator/factsheet/redlight.html.

49 Ibid.

50 Department of Homeland Security, *Standoff Radiation Detectors Market Survey Report,* National Urban Security Technology Laboratory (2013).

51 W.C. Thompson, *One Year Later - The Fiscal Impact of 9/11 on New York City,* Report by the Comptroller of the City of New York, 2002.

52 A.Baker, "City Would Photograph Every Vehicle Entering Manhattan and Sniff Out Radioactivity," The New York Times," (2008).

53 R.Stone, "Researchers Rise to the Challenge of Replacing Helium-3," *Science.* **353**, 15-16 (2006).

54 A.D. Lavietes *et al.,* "Technical Review of the Domestic Nuclear Detection Office Transformational and Applied Research Directorate's Research and Development Program," *IEEE Access* **1 ,** 661–690 (2013); J. Medalia, *Detection of Nuclear Weapons and Materials: Science, Technologies, Observations*, Congressional Research Service, R40154 (2010).

55 Department of Homeland Security, *Personal Radiation Detectors (PRDs) and Spectroscopic PRDs Market Survey Report,* National Urban Security Technology Laboratory (2017).

56 Department of Homeland Security, Domestic Nuclear Detection Office, FY 2018 Congressional Budget Justification, (2018), available at: https://www.dhs.gov/sites/default/files/publications/CFO/17_0524_Domestic_Nuclear_Detection_Office.pdf .

57 Metropolitan Police Department, Annual Report (2016), available at: https://mpdc.dc.gov/sites/default/files/dc/sites/mpdc/publication/attachments/MPD%20Annual%20Report%202016_lowres.pdf#page=41.

58 M. Schear *et al.,* "Monte Carlo Modeling and Experimental Evaluation of a 6LiF:ZnS(Ag) Test Module for Use in Nuclear Safeguards Neutron Coincidence Counting Applications (IAEA-CN--220)," Symposium on International Safeguards, International Atomic Energy Agency (2015).

59 G. J. Herrera, J.A. Dechant and E.K Green, "Technology Trends in Small Unmanned Aircraft Systems (sUAS) and Counter-UAS: A Five-Year Outlook," Institute for Defence Analyses (2017).

60 Centers for Disease Control and Prevention, *Injury Prevention & Control: Motor Vehicle Safety – Invention Fact Sheets for Automated Enforcement* (2015), available at: http://www.cdc.gov/motorvehiclesafety/calculator/factsheet/redlight.html.

61 K. Guthe, "The Global Nuclear Detection Architecture and The Deterrence of Nuclear Terrorism."

62 Government Accountability Office, Combating Nuclear Smuggling: Risk-Informed Covert Assessments and Oversight of Corrective Actions Could Strengthen Capabilities at the Border, GAO-16-191T (2015).

63 L. Zaitseva and F. Stienhausler, "Illicit Trafficking of Weapons-Usable Nuclear Material: Facts and Uncertainties," *Physics & Society*, American Physical Society, vol. 33, no. 1 (2004).

64 K. Guthe, "The Global Nuclear Detection Architecture and the Deterrence of Nuclear Terrorism," Multimodal Integrated Safety, Security and Environmental Program Strategy, Transportation Research Board, 87th Annual Meeting, 08-2644 (2008).

65 National Nuclear Security Administration, *Preventing Proliferation of Nuclear Materials and Technology* (2011), available at: https://nnsa.energy.gov/mediaroom/factsheets/dnnfactsheet2011.

66 K. Guthe, "The Global Nuclear Detection Architecture and The Deterrence of Nuclear Terrorism."