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DETECTION TECHNOLOGY IN THE 21ST CENTURY: THE CASE OF NUCLEAR WEAPONS OF MASS DESTRUCTION

BY

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From the time of the first nuclear detonation by the Soviets after World War II until the fall of the USSR and the declaration of victory in the Cold War, it has been nuclear WMD that have held the spotlight in American foreign policy. WMD were briefly placed on the back burner as the nation enjoyed its “peace dividend” at the end of the century. The events of September 11, 2001, were a wakeup call to America about the reality of the New World Order. Unlike the Cold War period, in which the primary threat was a massive Soviet nuclear attack or annihilation from an escalating war between nation-states, the post-Cold War era has been marked by the rise in the number of rogue states, failing states, and the emergence of non-state actors with both the means and desire to acquire and use WMD. Overcoming these challenges has become the center of American force planning and military strategy. What has become clear in all of these changes over the last decade is that proliferation and deterrence have increased in importance as strategic issues in the security paradigm. The two pillars of American deterrence policies, retaliation and denial, rely on the ability to detect the presence of nuclear material and attribute it to a particular origin. In the new strategic environment, this ability has become the cornerstone of deterrence. This paper will discuss the current and emerging technologies that make possible the direct detection of nuclear and radiological materials or devices that might become, or are already part of a WMD. It will also put forth recommendations for the future direction of development that will best accomplish the strategy stated above.

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DETECTION TECHNOLOGY IN THE 21ST CENTURY: THE CASE OF NUCLEAR WEAPONS OF MASS DESTRUCTION

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ABSTRACT

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this ability has become the cornerstone of deterrence. This paper will discuss the current and emerging technologies that make possible the direct detection of nuclear and radiological materials or devices that might become, or are already part of a WMD. It will also put forth recommendations for the future direction of development that will best accomplish the strategy stated above.

DETECTION TECHNOLOGY IN THE 21ST CENTURY: THE CASE OF NUCLEAR WEAPONS OF MASS DESTRUCTION

CHAPTER I: INTRODUCTION TO THE PROBLEM OF WEAPONS OF MASS DESTRUCTION AND DETERRENCE IN THE 21ST CENTURY

Introduction. According to many military historians, weapons of mass destruction (WMD) are not a phenomenon restricted to the modern era, having been used as early as 1347 by the Tatars during the siege of Caffa.[1] The Tatars used catapults to hurl plague-infested dead bodies over the walls. One million men were wounded and more than ninety thousand died from poison gas in World War I.[2] In the 1930s, the Italian Army gassed Ethiopians and Japan launched more than 800 gas attacks in its invasion of China.[3] In World War II, the casualties from the use of WMD could have been even more catastrophic. German factories were capable of producing approximately eleven thousand tons of poisonous gas per month. The British biological warfare project was years ahead of the Germans, producing five million cattle cakes packed with anthrax. Even the United States had a plan to use the anthrax bomb against Germany.[4]

The term WMD, however, has been the subject of much debate and confusion, especially within the government. There are numerous definitions of WMD (more than 40 are currently in use at the state and/or federal level) with some official or semi-official standing, although most are variations of one of five basic definitions. In fact, even the Department of Defense (DOD) has adopted alternative and fundamentally inconsistent definitions; including some different from the one used by the White House in its strategy and policy documents.[5] This paper will use the United Nations' standard definition, adopted in 1948 and used in three international treaties to which the United

States became a party (the Outer Space Treaty, the Seabed Treaty, and the Strategic Arms Reduction Treaty):

> [WMD are] … atomic weapons, radio active material weapons, lethal chemical and biological weapons, and any weapons developed in the future which have characteristics comparable in destructive effect to those of the atomic bomb or other weapons mentioned above.[6]

From the time of the first nuclear detonation by the Soviets after World War II, however, until the fall of the USSR and the declaration of victory in the Cold War, it has been nuclear WMD that have held the spotlight in American foreign policy. Decisions regarding contentions between American and Soviet alliance partners, and nearly every other international issue were couched in terms of the possibility of a nuclear World War III and the countless casualties within America's borders and the borders of its allies that might result. WMD were briefly placed on the back burner as the nation enjoyed its "peace dividend" at the end of the century. Even with the Iraqi invasion of Kuwait in 1990 and the resulting Persian Gulf War, most Americans believed that the end of the Cold War made the threat of a nuclear war nearly obsolete.

The events of September 11, 2001, were a wakeup call to America about the reality of the New World Order. The release of the *Nuclear Posture Review* (NPR) in 2002 by the Department of Defense articulated the truth of the situation[7], citing the new and multiple threats comprising the security environment of the twenty-first century. Unlike the Cold War period, in which the primary threat was a massive Soviet nuclear attack or annihilation from an escalating war between nation-states, the post-Cold War era has been marked by the rise in the number of rogue states, failing states, and the emergence of non-state actors with both the means and desire to acquire and use

WMD. The U.S. intelligence community has long reported that al-Qaeda is attempting to acquire this type of weapons capability. Documents and interrogations from military operations in Afghanistan have reinforced the assessment that the Taliban sought, and al-Qaeda continues to seek to develop biological weapons and obtain radioactive material for a radiological weapon.[8]

The huge quantities of weapons-usable fissile material in Russia (there is currently enough fissile material to build 60,000 nuclear warheads)[9], the smaller but terrorism-significant stocks remaining in Ukraine, Belarus, Uzbekistan, and other former Soviet and Eastern European states, and the unknown amounts of highly enriched uranium (HEU) and plutonium in North Korea and other countries greatly increase the risk of nuclear terror. States and terror organizations could acquire such material by purchase, diversion, or force for the purpose of fabricating a crude nuclear bomb, known more formally as an "improvised nuclear device" (IND). Steven Miller, Director of the International Security Program at the John F. Kennedy School of Government at Harvard University, believes the opportunities for well-organized and well-financed terrorists to infiltrate a Russian nuclear storage facility are greater than ever, and that there have already been more than two dozen thefts of weapons-usable materials in the former Soviet Union in recent years.[10] According to Miller, it almost happened again in 1994, when 350 grams of plutonium were smuggled on board a Lufthansa flight from Moscow to Munich. Fortunately, SWAT teams confiscated the material as soon as it arrived in Munich.[11] The nuclear smuggling network set up by A.Q. Khan and his international partners also demonstrates the relative ease by which nuclear material and technology can be obtained illicitly.[12]

Deterrence. Overcoming these challenges has become the center of American force planning and military strategy. President Bush reemphasized this point in the 2002 *National Security Strategy*[13] and its counterpart, *The National Strategy to Combat Weapons of Mass Destruction*[14]. He identified the threat of WMD in the hands of radical groups as "the gravest danger our nation faces…"[15] Both of these documents acknowledge that current methodologies utilized in deterrence have been imperfect. The strategies outlined, however, still focus on the widely accepted premise that rational state actors will be sufficiently deterred because of our substantial nuclear arsenal and the threat of retaliation. This "rational actor theory" has been the policy approach for the United States throughout the Cold War, and there are many who believe that the fact that the U.S. has not had to use nuclear weapons since World War II is evidence that the deterrence policy works. The policy was established on the confident assumption that foreign leaders would behave rationally when faced with the threat of U.S. nuclear retaliation, but information uncovered since the end of the Cold War clearly refutes this assumption.

Soviet leaders viewed nuclear weapons far differently than their American counterparts, and Soviet war plans for Europe included the early and heavy use of nuclear weapons.[16] Mistaken assumptions about the threat of global conflict and its ability to deter China from entering the Korean Peninsula on behalf of North Korea, or to deter the Soviets from placing missiles in Cuba are other examples of the fallibility of the rational actor theory. In addition, the U.S. has looked at normative constraints such as the Missile Technology Control Regime and assumed that no country that currently had ICBMs would violate this agreement and proliferate their missile technology.

Unfortunately, both China and Russia have demonstrated their willingness to do so in pursuit of their economic and political goals.[17]

Non-state actors, especially millenarian and radical religious extremist groups, are even less deterrable and will have to be handled differently. Globalization and the dropping of barriers through free trade agreements have facilitated the uninterrupted flow of many things, both good and bad, among countries. In addition, globalization has made all forms of WMD increasingly available to these groups.[18] The information required to construct these weapons has become commonplace, especially on the internet. For example, for $28.50, any internet surfer, including terrorists, can purchase the book *Bacteriological Warfare: A Major Threat to North America*, which explains how to grow deadly bacteria that could be used in a WMD.[19]

With the rise in the number of armed groups operating outside of the traditional nation-state, the ability of the United States to deter aggression through the 'traditional' threat of retaliation is diminished. In his article, "The New Threat of Mass Destruction", Richard K. Betts states that "[weapons of mass destruction] no longer represent the technological frontier of warfare. Increasingly, they will be weapons of the weak-states or groups that militarily are at best second-class."[20] These groups have no fixed infrastructure or other easily identifiable target, reducing the ability of the United States to use credible threats of retaliation for deterrence.

What has become clear in all of these changes over the last decade is that proliferation and deterrence have increased in importance as a strategic issue in the security paradigm. The two pillars of American deterrence policies, retaliation and denial, rely on the ability to detect the presence of nuclear material and attribute it to a particular origin. The U.S. leadership has recognized these changes in the security equation. The 2006 National Security Strategy of the United States acknowledges that:

> "The new strategic environment requires new approaches to deterrence and defense. Our deterrence strategy no longer rests primarily on the grim premise of inflicting devastating consequences on potential foes. Both offenses and defenses are necessary to deter state and non-state actors, through the denial of the objectives of their attacks and, if necessary, responding with overwhelming force."[21]

More important to strategic leaders today are the methods of detection, deterrence tactics, and defense options available to the National Command Authority. The detection of nuclear or radiological weapons of mass destruction (NRWMD) shares many features of the more general case of the detection of WMD. In the new strategic environment, the ability to detect the presence and track the origins and movement of nuclear and radioactive material has become the cornerstone of deterrence. There are many technologies for the detection of people and vehicles that might be transporting materials or devices for WMD. They exploit acoustic, seismic, optical, radio frequency and other mechanisms, which indirectly provide information on WMD. These non-specific technologies can be very important for overall defense, but are not within the scope of this report. In addition, many of the technologies in development for the forensic attribution of a nuclear device are currently classified. The materials and techniques may also involve information and methods that have had neither domestic nor international exposure nor validation in any public manner. What is clear is that the present actors and expertise for nuclear attribution are within the national security components of government and will continue to reside there for the foreseeable future. For these reasons this paper will not cover forensic attribution technology in any detail.

This paper will discuss the current and emerging technologies and policies that make possible the direct detection of nuclear and radiological materials or devices that might become, or are already part of a WMD. It will also put forth recommendations for the future direction of development that will best accomplish the strategy stated above.

CHAPTER II: CURRENT FORENSIC DETECTION TECHNOLOGIES

Terrorist use of radioactive nuclear materials is a serious threat for mass destruction or disruption of civil and military activities. Most worrisome is the use of nuclear devices to cause massive casualties to people and damage to structures. Fortunately, the procurement of adequate material and the engineering design, construction, and transportation and triggering of a nuclear weapon are all difficult problems for terrorist organizations. More likely is a device that combines radioactive materials with conventional explosives to make a radiological dispersion device (RDD), commonly called a 'dirty bomb'. The procurement of nuclear materials for this purpose, the construction of the bomb and its use are all easier than for a nuclear weapon. Fortunately, the effects from the use of a dirty bomb would be much smaller than from a nuclear device, although they could still be very disruptive. Thus, it is important to detect the transport of nuclear weapons and radiological dispersion devices and the materials for their construction. These materials emit gamma rays or neutrons, which can be detected to show the presence and amounts of such materials.

Geometry, air attenuation, and background radiation from natural and man-made sources determine the limits of detection of these materials. The natural gamma-ray background is a combination of three variables: terrestrial, atmospheric, and cosmic ray induced gamma rays. The natural neutron background is mostly due to cosmic-ray interactions with the air, the ground and massive objects such as buildings, ship superstructures, and cargo (a phenomenon known as the "ship effect" since it was first observed in the neutron signal from large ships.) Since the cessation of atmospheric nuclear testing, man-made background due to fallout has declined to levels well below the natural background. Except in regions contaminated by nuclear accidents, such as Chernobyl, or by an occasional lost medical or industrial radiation source, man-made background will not be an appreciable contribution to the radiation background.[22]

All nuclear detection technologies are designed to detect emissions from the decay of radioactive nuclides, which can occur naturally, such as uranium and thorium, or are manmade, such as plutonium and various fission products produced in a nuclear reactor. The primary long-range observables from nuclear materials are gamma rays and neutrons, which have average free paths of the order of a hundred meters in air and only ten centimeters in water. Table 1 shows the range of nuclear particles in various environments.[23]

Table 1. Range of Nuclear Particles

	Energy (keV)	Range (m)			
		In Air	In Water	In Aluminum	In Lead
alpha particles	5000	0.05	$6x10^{-5}$	$3x10^{-5}$	$2x10^{-5}$
beta particles	1000	4	0.004	0.002	$7x10^{-4}$
x-rays	10	1.9	0.002	$1.4x10^{-4}$	$7x10^{-6}$
	30	30	0.03	0.004	$3x10^{-5}$
gamma rays[a]	100	50	0.06	0.02	$1.7x10^{-4}$
	400	80	0.09	0.04	0.004
	1000	120	0.14	0.06	0.013
neutrons[b]	1000	200	0.1	0.1	0.08

[a]X-rays and gamma rays do not have a well-defined range. The table gives the average attenuation length or mean free path.
[b]The table gives the measured attenuation length for fission energy neutrons.

Radiation detectors have two applications toward nuclear and radiological weapons of mass destruction. The first is to intercept nuclear materials and devices prior to a terrorist attack. The second is for assessment and attribution after an attack. Such detectors represent relatively mature technologies. The first portable radiation instruments were developed more than fifty years ago in response to the use of nuclear weapons in World War II. Modern electronics and detector materials have made them much more capable. Now, new materials are being developed to enable even more efficient detection of gamma rays and neutrons with simpler devices. In recent years, large systems for imaging of gamma rays from nuclear materials and devices have been developed. Many passive and active, fixed and portable instruments for the detection of gamma rays or neutrons are available commercially.[24]

For realistic source strengths and available gamma-ray and neutron detectors from currently fielded technology, nuclear materials and devices can be detected at ranges of a few meters up to a few tens of meters. It is necessary to quantify the limits of utility for specific nuclear radiation detectors under the circumstances in which they are likely to be used. Several factors are involved in determining if nuclear material or a nuclear weapon is detectable above the natural background radiation, including the material/weapon configuration, the amount of shielding, type of detector, the level of background radiation, distance from the source, and the counting time. A good rule of thumb is that the signal from the weapon is detectable if it is greater than three times the standard deviation in the signal. (Standard Deviation, or Sigma, is equal to the square root of the sum of the peak counts plus background counts in the region of the peak.) Table 2 shows how the detection range for Weapons Grade Uranium (WGU) and Weapons Grade Plutonium (WGPu) weapons varies with counting time, detector size (or number of detectors) and source strength.[25]

Table 2. Detection ranges for hypothetical nuclear weapons

	WGU gamma ray emitting weapon			WGPu neutron emitting weapon			
number of detectors[a]	counting time (s)	gamma-ray source(s^{-1})	range (m)	detector area(m^2)	counting time (s)	neutron source (s^{-1})	range (m)
one	100	100,000	9.5	1	100	400,000	5.2
one	1000	100,000	19.2	1	1000	400,000	11.8
two	1000	100,000	23.1	2	1000	400,000	14.5
ten	1000	100,000	34.1	10	1000	400,000	22.4
one	1000	1,000,000	53	1	1000	4,000,000	35.2
one	1000	46,300[b]	13.4	1	1000	126,000[c]	6.7

[a]100% relative efficiency Ge detectors
[b]100,000 s^{-1} source shielded by 1cm lead
[c]400,000 s^{-1} source shielded by 10cm polyethylene

Detection technologies are generally complex in both their design and employment. Production of a detection instrument requires the use of one or more sophisticated physical, chemical, or biological mechanisms. It also requires expertise in materials and in electrical and mechanical engineering. Detectors designed for field use require attention to thermal, vibrational, and other environmental factors, however, care needs to be taken that the complexity of design and fabrication does not translate into complexity of operation. User interface and training is important to minimize operator error, as well as proper care for the instrument, including routine maintenance and re-calibration.

There are currently two fundamental classes of means for detecting and assaying the materials that may be made into or already constitute an NRWMD. The first class is technologies to find and exploit some signature, which indicates the presence of nuclear or radiological material. Typically, these instruments exploit spontaneous radioactive emissions from nuclear materials, or emissions stimulated by x-rays, gamma rays, or neutrons. The second class of detection technologies involves finding NRWMD devices. They often involve the acquisition of images that reveal these devices from their shape or from surrounding materials. Very large radiography systems, using either high energy x-rays or gamma rays, can image the contents of an entire truck or sea container.[26]

The best detection equipment, however, will still not be effective, unless it is in the right place at the right time, and in the hands of trained inspectors. In an exercise reported by ABC News [27] a mock-up of a nuclear weapon, consisting of 15 pounds of depleted uranium shielded by a steel pipe with lead lining inside a suitcase, was transported by rail from Austria to Turkey, passing through multiple border checkpoints without being inspected. An x-ray or gamma-ray scan of this mock-up would have surely indicated something suspicious. It was then crated and shipped by sea from Istanbul to New York. There it passed through U.S. Customs on Staten Island without being stopped or the crate opened for inspection, although Customs reportedly has state-of-the-art x-ray and radioactivity detectors at this facility.

Current technologies for the detection of nuclear or radiological material include numerous hand-held devices using a variety of detection materials. Among the most common today are Gamma-Ray Detectors that use Sodium Iodide (NaI). These systems are made by many companies in the United States as well as the Netherlands. The average cost for NaI detectors is between $1,000 and $8,000 per unit. They were some of the first systems widely produced, and have relatively poor energy resolutions, limiting their use in situations with high background radiation or many closely spaced peaks. Semiconductor detectors were developed to overcome these limitations, including the ‘gold standard’ of Gamma-Ray detection, Germanium semiconductor diodes. Germanium (Ge) detectors allow for precise determination of peak energies, separation of close-lying peaks and detection of weak peaks in the presence of a strong background. The major disadvantage for Ge detectors is that they must be operated at low temperatures (less than 100K) to avoid excessive electronic noise. The detectors require several hours to cool down and therefore must be kept cool using Liquid Nitrogen (LN) to be in a ready state. The requirement for a steady supply of LN can be a logistical problem in remote locations. Mechanical refrigerator coolers are also available, but these are more suited to fixed locations, since they are relatively heavy and require electric power. In a transportable detector, refrigerators can run off car batteries, but these would require frequent recharging. The most widely used portable Ge detectors weigh between sixteen and thirty-two pounds and cost anywhere from $25,000 to $48,000 including the analysis software and laptop computer.[28]

There have been extensive efforts to develop Room-Temperature Semiconductor Detectors (RTSD) that can be used in place of Ge detectors. The Institute of Electrical and Electronics Engineers (IEEE) has led the way in promoting the development of RTSD, hosting bi-annual international workshops to investigate, promote, and evaluate various theories and developments in this arena. Three previously-evaluated alternatives are currently available commercially: cadmium telluride (CdTe), cadmium zinc telluride (CZT) and mercuric iodide (HgI). For CZT, the best efforts to date have produced detectors that, while significantly better than NaI detectors, are still a factor of ten poorer than Ge detectors in resolution efficiency. CdTe detectors are much more accurate, but only for a very small detector which would require close proximity to the radiation source. HgI detectors give greater stand off detection ranges, but with lower accuracy.[29]

Neutron detectors generally rely on converting the neutron energy to a charged particle that can be more readily detected. The most common detectors are gas-filled proportional counters, and come in a variety of sizes and configurations. Two gases are most widely used, boron fluoride (BF_3) or a helium isotope, (^3He). ^3He is more expensive, but it has a higher detection probability and ^3He tubes can be filled at high pressure to further increase detection efficiency. Gas-filled proportional counters are most sensitive to low-energy thermal neutrons, but the probability of detection decreases rapidly at higher energies. This requires a moderator to surround the detector, slowing down the neutrons by multiple scattering reactions. Moderators are usually materials, such as polyethylene, with high hydrogen content, since protons are the most efficient neutron scatterers. Other neutron detectors include an isotope with high thermal-neutron reaction probability, such as ^6Li (lithium 6) combined with a plastic or glass fiber scintillator.[30] (A scintillator is a substance that absorbs high energy (ionizing) electromagnetic or charged particle radiation then, in response, fluoresces photons at a longer, measureable wavelength, releasing the previously absorbed energy). These have the advantages that they can be made in any shape and size and they have relatively high thermal-neutron detection efficiency when compared to other neutron detectors. Bubble detectors are a newer system that uses a unique neutron detection technology that consists of small droplets of superheated liquid inside a pressurized gel-like polymer matrix. Neutron interactions cause the droplets to expand into small gas bubbles, which remain trapped in the gel. Cumulative neutron exposure can be obtained simply by counting the bubbles. Real-time readout can be achieved by observing a change in the light transmission of the gel or by using an acoustic sensor to detect the bubble formation.[31]

There are nearly twenty different portable survey and multi-channel analyzers (MCA) currently in commercial use for forensic detection and analysis. Of these, only two, the MICROSPEC and the IDENTIFIER, are manufactured outside the United States (both are made in Canada). Portable MCAs generally combine the functions of an amplifier, MCA, and power supply in a small package, which interfaces with a handheld detector. Some recent models offer a complete package with a built-in NaI, CZT, or Ge detector and nuclide identification software.[32] These instruments range in size from less than one pound to twenty-five pounds, and can detect all sources of radioactive material, depending on the model.

Pedestrian and vehicle portals for detecting nuclear materials combine large plastic scintillators of NaI gamma-ray detectors with gas-filled neutron detectors. These are contained in pillars similar in configuration to airport metal detectors. Mobile nuclear search systems typically contain large NaI detectors and ^{3}He neutron tubes mounted in a van or car top container. These have been used for some time by the US Department of Energy (DOE) and are now commercially available.

Imaging detectors can be either passive, looking at the natural emissions from the target material, or active, using high-energy x-rays or gamma rays to image the target. Imaging improves the signal to background ratio, since the target generally covers a small field of view while the background tends to come from all directions. Astronomers have led the development of passive imaging techniques for gamma-ray astronomy. Coded-aperture imaging uses a computer designed filter and software reconstruction to produce an image.[33] This technology works extremely well at lower energy levels, but the filter has problems stopping the gamma rays at higher energy output. Another technology, Compton imaging, has been developed to deal with the higher energy materials. It works without a filter, using the physics of gamma-ray scattering in the detector to reconstruct the image. One of the more common passive imaging detection systems in use today is the GammaCam™ imaging system, which employs the coded aperture technique. It has been used by DOE to image relatively high-activity sources at the Hanford, WA facility and at Argonne National Laboratory in Argonne, IL.[34] This is particularly good technology for imaging hot spots in a high radiation background, but is less capable for imaging the relatively weak attenuated signal from a shielded weapon. The Soviets developed a similar passive imaging system, and successfully tested it in 1989 by mounting it to a helicopter flying over the Black Sea. In the test, the helicopter measurements were made at ranges from 30 to 75 meters from the ship. The detectors were ^{3}He tubes in a moderator and detected the neutrons from the spontaneous fission of the plutonium used in the experiment. The detector took only ten seconds to detect the material, and the overall detection probability exceeded 95%.[35]

Active imaging systems, however, use a high-energy x-ray, gamma-ray, or neutron source to penetrate low atomic number materials to obtain a transmission image of imbedded uranium or plutonium. They may also be used to image stimulated emissions of neutrons and gamma rays, which are induced in nuclear materials by the interrogation source radiation. These systems typically employ a scanning procedure in which the source and detectors move along together along either side of the vehicle being inspected. The U.S. Customs Service uses the EAGLE™ cargo inspection system, which employs active imaging using transmission x-ray technology, which can penetrate up to 30 centimeters of steel and image a highly shielded weapon. The manufacturer has signed a Cooperative Research and Development Agreement (CRADA) with two DOE laboratories to use this system for imaging photo-fission induced neutrons and gamma rays from nuclear materials. Other systems being used currently in securing transportation terminals into the United States include the VACIS™ transmission gamma-ray imaging system, which uses high-energy gamma rays to image a vehicle, and the Shaped-Energy™ x-ray system, which uses an x-ray beam and detects both transmission and backscatter x-rays from the cargo to form dual sided images. This system can simultaneously detect gamma rays and neutrons emitted from the cargo during the scan.[36]

Most current detector systems display the information they capture on or near the detection units. However, the growing need for an integrated deterrence and the consensus that a layered security system offers the best option in combating WMD threats has made wireless connectivity to remote locations, such as command centers, increasingly essential. One example of a newer gamma ray detection system is the MOBILE DEFENDER™. It contains a NaI detector and associated electronics, plus a radio that can transmit information on the output of the detector, all within a small case.[37] This system was employed at the Athens Olympics in 2004. It can also be fitted with sensors for chemical and biological detection. The integration of multiple sensors into one detection system permits sharing of power supply, computer and communications sub-systems. Another unique portable system, the PIRATE, provides a compact, secure wireless communications platform for hazardous material analysis. It can be equipped with sensors for nuclear, chemical or biological materials, GPS, a graphical interface, and image recognition software.[38]

CHAPTER III: DETECTION TECHNOLOGIES IN DEVELOPMENT

Within the scientific community there has already been a program in place to highlight and focus on the development of new technologies with nuclear detection applications. As mentioned earlier, the most effective semiconductor technologies require extremely cool temperatures for best results (100K). The IEEE's bi-annual workshops have been integral to the development of new RTSD systems. These technologies are finding increasing applications in such diverse fields as astrophysics, nuclear medicine, and environmental remediation, as well as national security. The IEEE forum of scientists and engineers from all over the world is working on the development of new solid-state radiation detectors and imaging arrays.

Some of the developmental technologies are showing tremendous promise. Part of the work has been focused on growing larger single crystals in order to make more efficient gamma ray detectors with a much larger energy bandwidth within which they can provide accurate results. Another technology showing promise uses high-pressure xenon detectors.[39] A new scintillator using lanthanum chloride ($LaCl_3$) is available with properties similar to NaI, but with superior resolution capabilities.[40] Other new scintillators, such as lanthanum bromide ($LaBr_3$) are under development with resolutions more than twice as accurate as the standard NaI detectors.[41] A very compact, low-power, mechanically-cooled Ge detector system has reached the prototype stage using a miniature Stirling-cycle cooler. This instrument is designed for long shelf life in the field and contains peak analysis software and nuclide identification using a stored gamma-ray library. The prototype can operate up to nine hours using a rechargeable lithium ion battery.[42] Compact Compton and coded aperture gamma-ray imaging systems are being developed using segmented Germanium detectors to obtain greater sensitivity, high energy resolution, and good angular resolution.[43]

In addition to the advancements underway in gamma ray detection, neutron detection technology is also exploring new possibilities. Ongoing research in neutron detectors is focused on solid-state detectors to replace gas-filled tubes. The approach here is to make use of neutron-capture reactions to convert the neutron into an energetic charged particle, which then can be detected by solid-state detectors. A converter material is used such as boron ten (^{10}B), which has a high thermal-neutron capture cross-section and emits energetic charged particles following capture. Efficiencies are being achieved that are three to five times higher than previous technologies.[44] Under a grant from the Defense Threat Reduction Agency, another company is experimenting with the development of silicon carbide neutron detectors that will increase response times and reduce vulnerabilities to both large gamma influences and adverse temperature conditions.[45]

An innovative imaging technology under development uses scattering of cosmic-ray muons to image high atomic number materials, such as uranium and plutonium. (A muon is an elementary particle with a negative charge formed by naturally occurring cosmic ray collisions with molecules in the upper atmosphere). The developers estimate that a border detection system could be built to detect a ten-centimeter cube of uranium in one minute.[46]

Of all the technologies in development, active interrogation holds the most promise for detecting heavily shielded materials at a distance. This process involves using an external radiation source to excite detectable reactions in the target being inspected.

Special Nuclear Material (SNM) that is present will undergo fission reactions that generate prompt and delayed gamma rays and neutrons that can be detected. Pulsed beams allow the detection of delayed gamma rays or neutrons from fission products between pulses. Various tests have shown that the technology to interrogate suspected SNM with a high flux of gamma, proton, and/or muon particles over large distances (kilometers) has been developed to the prototype stage. Megawatt power accelerator technology has been designed and built.[47] The technologies have been advanced to the point that long-range/standoff detection of SNM at sea and even in the air are not out of the realm of possibility. However, the biggest technological challenge is the detector placement, as it is still necessary to have the detector placed close to the target to accurately identify the presence of SNM. Many different methods have been proposed to generate interrogation particles, but the two most promising are neutron and photon radiation sources.

Photon Interrogation. Investigation and assay of high atomic number materials may be accomplished in near real-time through use of photon interrogation. Photon interrogation, involves the use of high-energy photons to induce fission and then detect neutrons associated with the fission. This technique has the advantage that the interrogating particle and the detected particle are different, reducing the possibility of false readings. A linear electron accelerator is commonly used to generate the photon beam. The other advantages of photon interrogation are near real-time results, accountability of both prompt and delayed neutrons depending on matrix used (pulsed beam), and the availability of both radiography and therapy accelerators to generate the photon beam. The challenges being worked involve the accuracy of distinguishing between fission and fertile material; and the need for the interrogated material to be well characterized (a known substance).[48] The Idaho National Laboratory, along with the Los Alamos National Laboratory and the Idaho State University's Idaho Accelerator Center, are working on these and other challenges in developing photonuclear inspection technologies for detecting shielded nuclear material within air, rail, and especially, maritime-cargo transportation containers.

Neutron Interrogation. In a study conducted at the Lawrence Livermore National Laboratory, scientists identified a new radiation signature unique to SNM that utilizes high-energy fission product emissions. This new signature is robust in that it is very distinct compared to normal background radiation where there is no comparable high-energy radiation. Equally important, it has a factor of ten higher yield than delayed neutrons, and it readily penetrates two meters of low-density and high-density cargo. Finally, unwanted collateral effects of the interrogation such as neutron activation of the cargo have been analyzed. Even in the worst case the dose rates resulting from activation are well within limits for radiation workers within minutes after the end of irradiation and in most cases drop to levels acceptable for exposure of the general public within minutes or hours. In all of the case studies so far, the activation levels of cargo, even under the worse case assumptions, are low enough for the cargo to be considered non-radioactive for shipping by the Department of Transportation.[49]

To make passive and active detectors more ubiquitous and useful, advances in scintillator material are also being developed. A key goal is to combine the best performance characteristics of the current technologies within a single material. One example is nano-composite material, made up of nano-sized particles of known insulating and semi-conducting scintillators. This material appears to offer improved energy resolution, due to the fact that nano-composites have reduced self-absorption and enhanced light-yield, along with improved lifetime. Because nano-materials are synthesized in a scalable way, significant cost savings compared to bulk materials is possible. The Los Alamos National Laboratory recently developed techniques to produce nano-material with dimensions up to about 1mm, and plans are under way to scale up the production process to larger sizes.[50] Another effort seeks to develop a new class of radiation detection materials called "composite inorganic semiconductor quantum dot/organic semiconductors." These materials will possess the cost and processing advantages of organic scintillators (low cost, ease of fabrication, and fast response times) and the ionization characteristics of inorganic semiconductors (high energy resolution and detection of strongly ionized particles).[51]

Finally, steps are being taken to improve the analysis algorithms used in the thousands of hand-held detectors already in use for radiation monitoring by first responders. One such algorithm, Material Basis Set, compensates for shielding impacts on gamma spectra, reducing the false alarm rate by nearly 75% while maintaining the detector calculation performance times at one second.[52]

CONCLUSIONS. The threat of nuclear or radiological weapons being used against the United States or its interests/allies remains the greatest danger the nation faces. Given the spread of nuclear weapons and technology, the United States will continue to require a credible nuclear deterrent posture, to include the extended security guarantees negotiated with other countries. This posture must be able to adapt in a timely fashion to new threats as well as new opportunities to reduce the threat. The ability of the United States and its allies to detect the movement and/or presence of SNM is critical to this credibility. As the organizational focal point for this mission, the Domestic Nuclear Detection Office (DNDO) is charged with improving the nation's ability to detect and report any unauthorized attempts to import, possess, store, develop, or transport nuclear or radiological material for use against the United States. The current global detection architecture has multiple integrated layers, including materials protection, control, and accountability, overseas border security, port of departure screening, overseas interdiction, Coast Guard inspections, and U.S. border protection. Each of the technologies discussed in this paper are currently in use or being developed for use in one or more of these layers. One of the key goals for this R&D thrust is to develop next generation passive sensors to enable 100 percent coverage of all official ports of entry, with mobile assets for other locations. There is also substantial investment in handheld and portable systems to support the Border Patrol and Coast Guard, commercial vehicle inspection, expanded surveillance for high-risk cities, and Federal surge capacity.[53] The bottom line is that the United States must be ready to respond to the complex and dynamic environment that currently defines WMD proliferation, and should continue to pursue the broadest range of research into detection technology. The nation is likely to be dealing with multiple proliferation challenges at any given time, and the ability to detect and attribute SNM will broaden the range of policy tools and tactics available to the decision makers as they seek to deter would-be proliferators and others who would use WMD against U.S. interests at home and abroad. While not discussed in detail here, the development of these technologies would enhance the ability of the United

States to trace nuclear use as a basis for assigning attribution and therefore strengthen extended nuclear deterrence. Improving the nation's forensic ability, together with the means of responding, would go far to help the U.S. update extended nuclear deterrence , especially the need to deter states from providing nuclear capabilities to terrorist groups by the ability to trace nuclear weapons or key components back to their source.[54]

Successful deterrence will require low-cost, large-area detectors that can locate and identify SNM and monitors for radiological isotopes that are more robust than current systems. Potential improvements can result from the recent advances in electronics, materials, and nanotechnology discussed in this paper. Enhanced data-analysis tools that reduce false alarms and increase detector accuracy will assist in closing the current gaps while improving the flow of goods across the international marketplace. Stand-off detection capabilities will greatly enhance the ability of the United States to further refine its concept of a layered defense at it relates to homeland security.

In conclusion, it is worth reiterating that the *National Security Strategy of the United States* identifies the threat of WMD as "the gravest danger our nation faces…"[55] It is both natural and sensible to deduce that the nation would bring to bear all elements of national power necessary to address this threat. To do otherwise would be to invite disaster on a scale beyond imagination.

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