A Guide for Detector Development and Deployment

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ABSTRACT

A more efficient process for developing and fielding new radiation detection technology is needed. Radiation detection systems are frequently installed and implemented based on immediate needs. This procedure often occurs without considering all the factors that will influence the ultimate effectiveness of the system. For instance, in major shipping ports portal radiation monitors are primarily made out of plastic scintillators and are placed at specific exits to detect illicit radioactive material. This placement of detectors helpfully minimizes their affect on port operations, but is it the most efficient placement and available technology for the mission? As new detector technology appears on the market, rather than simply replacing current detectors with new ones, a systems approach should be applied to most effectively deploy the new technology. Texas A&M University, through a grant from the Domestic Nuclear Detection Office, is developing a framework that will help evaluate new detection technologies and examine how to use that technology in the most efficient way. This paper focuses on the detection of shielded highly enriched uranium in large shipping containers. Our multi-disciplinary approach includes detector and transport code development and takes into account industrial engineering and socio-economic concerns. The presentation will highlight how new detector technology is incorporated into the framework and how both Monte Carlo and Deterministic simulations are used to optimize detector types and placement. Socio-economic studies will be described, as well has how best practices from the shipping port industry are taken into account.

INTRODUCTION

Radiation detection systems that monitor ports of entry are critical components to assuring that illicit radioactive materials do not enter the United States. Systems need to be thoroughly evaluated before they are installed. These evaluations should include examining the detection material, types of detection algorithms, the best placement and the socio-economic impact of potential detection methods. A grant funded by the Domestic Nuclear Detection Office Academic Research Initiative (DNDO ARI) at Texas A&M University is creating an organized method, or framework, for evaluating existing and future portal monitoring technology and determining the best placement of these systems. The difficulty of this project is further increased because it is focused on the detection of shielded highly enriched uranium (HEU) in cargo containers.

A multi-disciplinary, systems approach is being employed to develop the framework. Instead of focusing on just the type of detector being employed, this study looks at detection technology, system placement, integration into current port operations and social science/policy factors of specific scanning methods. To complete this task, new detection algorithms are being developed, new and existing radiation transport codes are being used, port best practices are being investigated and new types of detection technology are being examined. In addition, policy related issues are being investigated. Each of these disciplines will affect how a complete port of entry radiation detection system is implemented.

MULTI-DISCIPLINARY APPROACH

The process for developing this framework is separated into 4 different specialties. Each specialty is represented by research teams that complement each other in the development of the framework. A Detector Development Team is creating new radiation sensors and testing their validity within the framework. A second team, dedicated to Systems Analysis, assesses efficient work practices and policies for inspecting cargo for nuclear materials at ports of entry. The Radiation Transport Team responsibility is to develop simulations and techniques to accurately simulate radiation levels that can be expected in realistic scenarios. Lastly, the Social Science and Policy Team evaluates the policy related parameters that will impact successful implementation of a viable detector system.

Detector Development

Teams of electrical, chemical and nuclear engineers are researching novel approaches to radiation detection. Integrated circuits (ICs) are being explored as one avenue. Radiation hardened sectors on an IC have been developed and are paired with extremely radiation sensitive sectors. Radiation resistant areas act as watch-dog sectors. This radiation resistant portion will help register and quantify the temporary radiation damage that occurs on sensitive portions of the chip. To help synchronize processes on the chip, researchers have developed a circuit approach to harden clock regenerators on the chip. In an IC, the clock signal is very important, since it orchestrates the computation of all other portions of the chip. The effort has included device level simulations, developing techniques for radiation hardening, and techniques to intentionally increase the radiation susceptibility of components.

A similar approach being investigated uses a diode based detection micro array and control circuitry. This approach is loosely based on digital camera technology. It is hoped that using stacked arrays of these sensors that one will not only be able to detect incident radiation, but also determine source direction. Laboratory experiments have been conducted using Commercial-off-the-shelf (COTS) imaging sensors. The system was exposed to ^{241}Am, ^{137}Cs and ^{60}Co. Each source was shielded to stop any possible beta emissions from reaching the detector. The system registered gamma radiation at all three energy levels. Digital signal processing techniques are now being applied to the data to refine the signal.

Researchers are also investigating the use of new type of radiation detector that has a structure similar to the large-area flat panel computer displays. The principle is that the whole detector is divided into many interconnected pixels. Each pixel is composed of a charge storage device and a transistor. Prior to radiation exposure a charge is stored in each pixel. Once a pixel is subjected to a radiation field the amount of charge will be reduced. The change in the amount of charge is proportional to the radiation intensity. Since the information in each pixel is individually calculated, the distribution of the radiation intensity across the whole detector area, i.e., the radiation distribution, can be obtained.

There are several methods to build the above type of flat panel detector. Currently, we are fabricating a new floating-gate thin film transistor (TFTs). It can store and release charges according to the control (gate as well as the drain) voltage. It can be connected to a diode that is coated to a scintillation layer. The scintillation layer converts the radiation source to visible light, which discharge the stored charge on the diode. Then, the TFT is used to register the amount of charge released. The local radiation intensity is transformed to a charge loss. Therefore, a map of the radiation intensity distribution can be established.

There are many advantage of this kind of detector. It can be build into a large-area detector with very thin in dimension and light in weight. The operational power consumption is low. It can be attached to suspected container for long term monitoring.

A directionally sensitive neutron detection portal system is being investigated. ^{10}B is a common element used in the detection of neutrons. Following the absorption of a neutron, an alpha particle and ^{7}Li are emitted. In flight, the ^{7}Li will emit a 478 keV photon with a branching ratio of 94%. When viewing this reaction with a multichannel analyzer the photopeak is Doppler broadened [2]. To derive neutron directionality this system will take advantage of the Doppler broadening. Simulations have been developed for reactions of interest in a boron loaded solid state semiconductor detector. These models give various particle parameters such as energy, post-reaction scatter angle, and a rapid approximation of pre-reaction particle direction. To create a Doppler broadened de-excitation gamma ray, a computer code will be written combining output files from MCNPX's particle tracking parameter (PTRAC) in conjunction with the aforementioned simulation. This additional code needs to be created because MCNP and PTRAC lack the ability to Doppler broaden photons emitted from particles in midflight. As a result, the development of this code will benefit the broader MCNP community as well as this project. The detector substrate is being created through collaboration with the Naval Research Laboratory.

Systems Analysis Team

The Systems Team develops and analyzes models to obtain appropriate policies for inspecting cargo for nuclear materials at ports of entry. This team uses these inspection policies as building blocks in the analysis of global transportation networks.

The initial focus of the team was on containerized cargo entering the United States through sea ports. Inspection-related activities at a port were modeled using a queuing network model. In this queuing network, the nodes correspond to inspection stations (for example, a passive radiation portal monitor, or an x-ray system, or manual inspection). The containers move along this network, with routes being determined by the results of the inspections (alarm vs. no alarm). An overview of this inspection system is given in Figure 1. The first node, Radiography, has a number (m_R), of X-ray units to scan the containers at the port. It takes μ_R minutes to scan a container. If, at this node, the "hardness" threshold, t_R (amount of high Z materials in the container), is surpassed then it moves to the Active Node (neutron radiography). If t_R is not overcome then the container is moved to the Passive Node (passively scanning for radiation). If the Active or Passive Nodes have negative results then the container is moved to the Loading Node and is cleared for commerce. If the detector count rate at the Passive node exceeds its threshold, t_P, then the container is moved to Active for further scanning. When the threshold, t_A, at the Active Node is exceeded, the container is moved to the Manual Node where it is unloaded and eventually reaches the Detection Mode when the item is located.

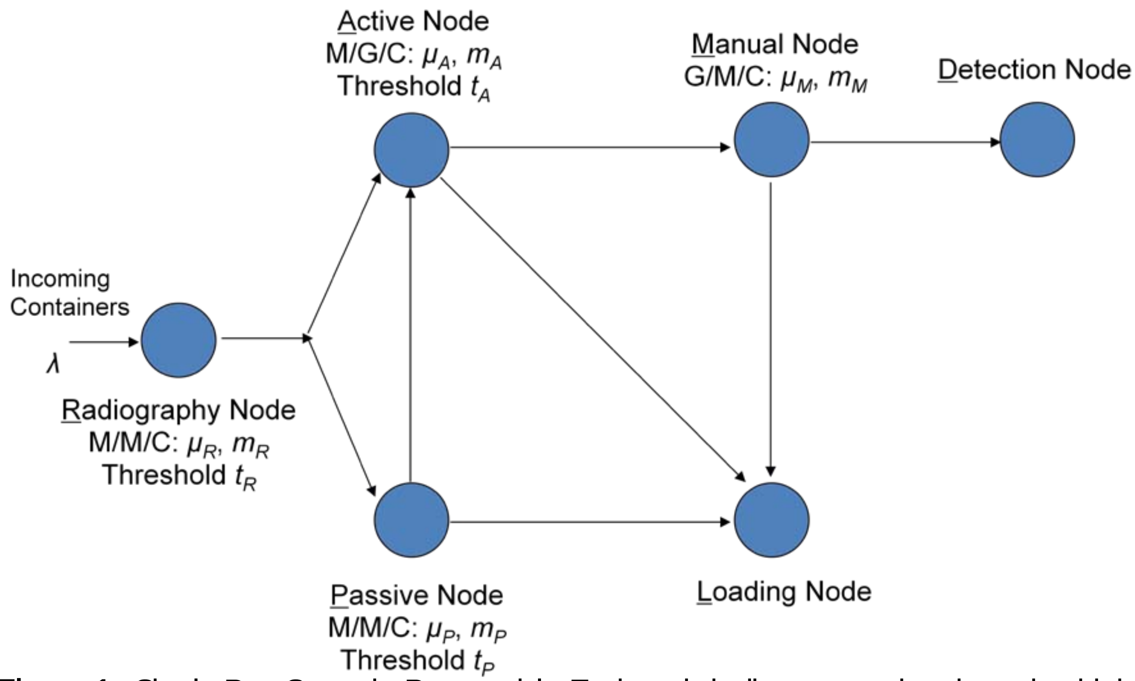

Figure 1. Single Port Scenario Port model. Each node indicates a station through which the container must travel in ordered to be cleared for commerce.

The performance measures of interest in this system are the detection probability (i.e., if there is a quantity of HEU in a particular container, what is the probability that it will be detected?) and the expected delay time of containers at the port-of-entry. This delay time is the sum of all inspection and waiting times for a container. The delay time is important to know, because it directly affects the flow of commerce through that port. Clearly, there is a trade-off between detection probability and delay time. The team has developed several inspection policies that prescribe how containers should be inspected, and which path among the inspection stations a particular container should follow. One inspection policy is designed to closely mimic the logic of the existing ATS (Automated Targeting System)-based inspection policies used at domestic and overseas ports. Another inspection policy was based on radiography results that obtain information on the material contents of a given container. The system analysis team interfaced with the Transport and Detector teams to evaluate the performance of these two policies for several container sample scenarios [3].

Beyond the single-port scenario, a port network model was developed, consisting of multiple foreign and domestic ports. In conjunction with work on the port network setting, adversary behavior was evaluated, and the effects of adversary decisions on the performance of an inspection system.

The port network model allows comparisons of different detector hardware deployment strategies and evaluation of the impact of budget decisions on the overall performance of the nuclear materials detection strategy. This network model also incorporated measurements and inspection results from upstream inspection stages (e.g., a foreign port) with the inspection policy in use at downstream ports of entry. Upstream inspection results can be used to fine-tune the inspection at downstream ports. However, there is a caveat: if upstream results are unreliable (that is, if they are questionable or even untrustworthy), then they should not be taken into account; the model demonstrates that if unreliable upstream information is taken into account downstream, they can decrease detection probability.

The adversary behavior analysis included the likelihood of an adversary being able to infiltrate certain cargo container types during the transit between ports. The evaluation illustrated that if the likelihood of infiltration in-transit is sufficiently low, upstream inspection results can be used beneficially at downstream ports; however, if the likelihood of infiltration is beyond a certain threshold, system performance is poorer than without using the upstream port's information.

The team's efforts contribute directly to building the framework of the overall project. The derived inspection policy models allow for the comparison of both different hardware (detectors), as well as different policy decisions (what to inspect, how much time to spend inspecting etc.).

Radiation Transport Team

This group is not only responsible for creating detector transport simulations, but also to model the different cargo scenarios that may be encountered. Two methods are being employed to complete the simulation process. The first employees the Monte Carlo code MCNPX. The second method involves the development of a new deterministic code called Parallel Deterministic Transport (PDT).

To date Monte Carlo N- Particle (MCNPX) is the only radiation transport code used to develop the framework. A typical cargo container of dimensions 20'x8'x8.5' with a 3mm steel wall is modeled using MCNPX. The cargo container was filled with a combination of different materials such as plastic, cotton, wood, concrete and steel. The container itself was divided into 32 boxes, which in turn was filled with the materials aforementioned to form a scenario. The objective for each scenario modeling is to compute the photon count rates in a detector kept outside the container but in proximity to its steel wall. A sodium iodide (NaI) crystal of dimensions 2"x4"x16" is incorporated directly into the cargo container model. Simulations are performed with 1 kg of HEU (70% ^{235}U) metal in one of the container boxes. In order to account for the background radiation simulation, a concrete slab of dimensions 50'x33'x1' is modeled 50 cm below the cargo container box. This slab currently has been modeled containing a uniform distribution of ^{40}K only. The activity selected is 385 mBq g^{-1} of concrete as suggested by NCRP-94 as the maximum among various concretes. To date over 50 simulations have been conducted with varied cargo composition and source positions. There are two important observations made from the MCNPX simulations of the cargo container scenarios. (1) When the cargo container is filled with a combination of even low density materials like plastic, wood and cotton, the signal to noise ratio obtained is very poor. (2) Even if the background radiation (noise) is reduced by some method the signal is too low which calls for very large detection times. This situation may be alleviated by bringing the detector closer to the cargo container and also introducing into the simulation the radiation streaming paths which would actually be present in between the container material box stacks. One disadvantage of using Monte Carlo codes such as MCNP is that the run-times for these models can take several hours to days to process.

To significantly accelerate computational activities a deterministic code can be used. PDT is a massively parallel, deterministic, neutral particle transport code that is being co-developed and upgraded for use on this project. PDT is coded in C++ which makes it readily portable across architectures ranging from laptops to supercomputers. It uses structured or arbitrary grids and contains a variety of discretization and iteration methods. It is designed to accommodate adaptive algorithms; and it can solve time-dependent or steady state problems [1]. Cross section libraries for PDT have been generated using the SCALE code. However, SCALE offers little flexibility in the neutron and gamma energy group structures when generating cross section sets. In this work, specific photon lines must be resolved and therefore the SCALE output must be adjusted to fit our requirements. Software is being written, outside of PDT, that will adjust the SCALE libraries and write new ones with different energy group structures. Once completed, it is hoped that PDT will significantly decrease computational time.

Social Science and Policy Team

Socio-economic concerns can affect how technology is implemented. It will cost a considerable amount of money to implement new detector technology or introduce new scanning methodology in both foreign and domestic ports. In addition, as new systems are brought on line the United States may insist that certain technologies be used at foreign ports. Will this affect international agreements? Will the public accept potential higher costs and transportation related delays? Will trade unions be supportive to changes in port operations? These areas are being examined by the Social Science and Policy Team.

The team produced and executed a national public survey to evaluate the public's concern on terrorism and homeland security issues. The survey focused on risk assessment of nuclear security, trust in government agencies in handling nuclear terrorism and national security, the support of various policy options and the willingness to accept costs for policy decisions. The key findings of this September 2009 Public Opinion survey were:

- The survey found moderate levels of attention and concern about terrorism/homeland security issues compared to other national issues.
- There was a broad and moderate support for various policy options proposed to deal with the issue of nuclear security and terrorism.
- Both Department of Homeland Security and Domestic Nuclear Detection Office received high marks on trust and competency.
- The public wants nuclear protections focused both abroad and at home.
- Perceived costs and policy actions were ordered somewhat by partisanship and ideology.
- The public are somewhat willing to accept higher costs and transportation-related delays, as well as some personal intrusion resulting from government activities to combat nuclear terrorism [1].

The team has also surveyed congressional activities (hearing and testimonies) as well as news media articles on counter nuclear terrorism and nuclear detection between 1990 and 2007 (Figures 2 and 3). As might be expected media and congressional attention to nuclear terrorism matters has

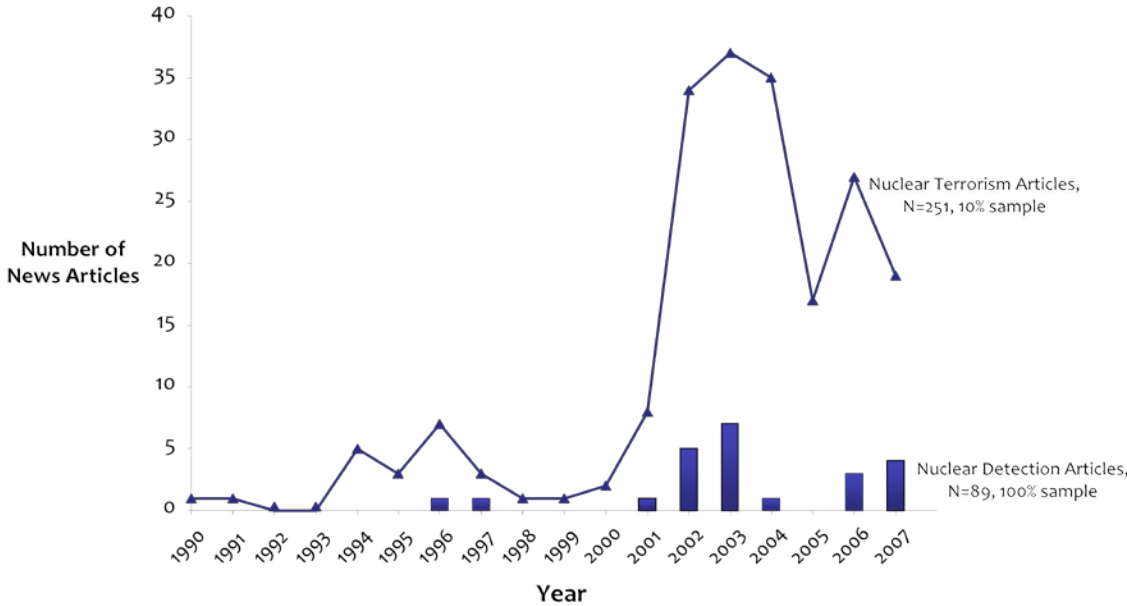

Figure 2. News media attention on both nuclear terrorism and nuclear detection issues. Increased activity is evident following the September 11, 2001 attacks.

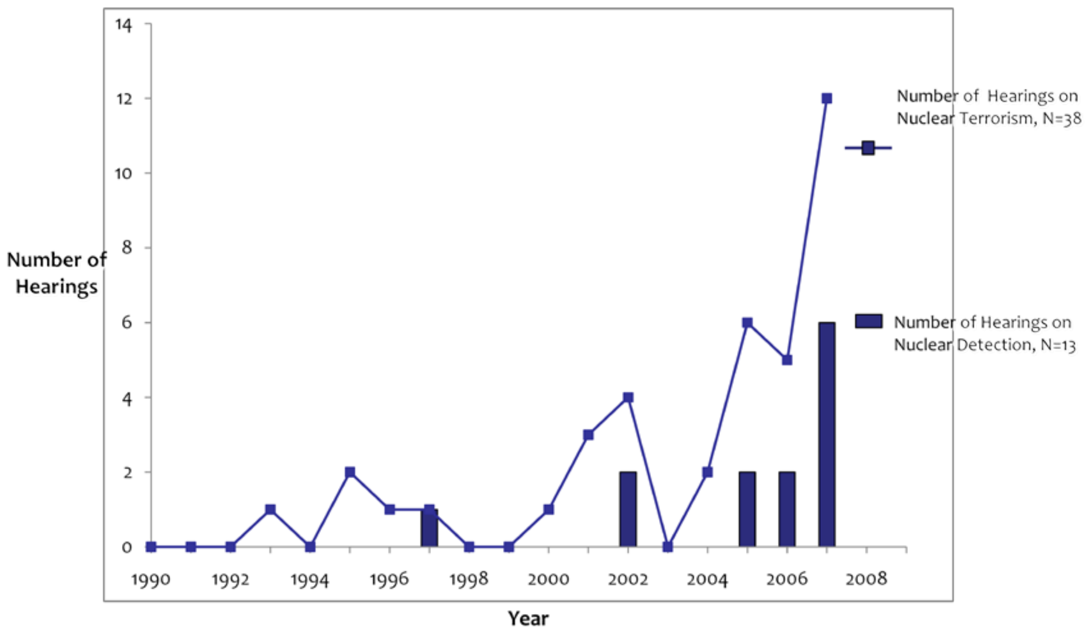

Figure 3. Congressional activity regarding nuclear detection and terrorism.

significantly increased since the September 11, 2001 attacks. There have been growing interests in nuclear detection and interception in both the news media and the government in the last several years. From studying the congressional record and news media three primary concerns regarding the nuclear detection technologies and programs were capacity building, technical reliability and program efficiency.

By continuing to compile this information the team hopes to interpret potential policy and social concerns into the application of new technology in port detection activities.

APPLYING THE FRAMEWORK

The work that is being described here is a framework of how detector technology should be evaluated prior to installation. The end product will not be a computer program that a novice user can just enter in information. It is a method that can be followed and will provide a useful measure of the technology in context to the mission it is to perform. It is envisioned that at the end of this work that DNDO will have a tool to evaluate proposed technology before it is put in place.

The following is an example of how the framework will be applied once it is completed. Suppose a new detection technology has been developed to passively detect HEU in shipping containers. It is proposed that this new system will replace the portal monitors at ports of entry in the United States and its protectorates. To assess and develop a detection concept for this scenario, we begin by modeling the detector response. Several simulations of the new system are carried out based on different packaging, source placement and background scenarios. This simulation will then determine the expected signal from the detector, which typically is composed of count rates with some information concerning energy, time, angle, and possibly radiation type. By comparing the background response to source with background response an acceptable false alarm rate can be established. Typically this rate would be a function of scanning time which the cargo container is exposed to. Taking into account the false alarm rate, expected delays associated with scanning time and current ATS practices, the detection efficiency as a function of delay time can be established. Delay time being how long the cargo is in transit in port operations. The political and social sciences node would digest the information from the other nodes: detector system, apparatus placement, false alarm rate, detection efficiency and delay time and determine if there are any implementation issues that could arise (international agreement, union issues, socio-economic issues). This full evaluation would produce a measurable result that could be compared to current or future systems.

If anywhere along this process issues arise that show the technology to be unacceptable, adjustments can be made in upstream nodes. For instance, if the political science node had an issue with the system, it would be passed back up to the detector or systems mode to see if adjustments (system placement, scanning time, etc.) could be made to make the system more effective. This in turn could create the need for further simulations. This would not be a static process, but a dynamic process. This approach results in detector development based not only on the direct use of signals within a single information analysis arena but also on considering the global implementation of the detector system.

CONCLUSION

Radiation detection systems are frequently installed and implemented based on immediate needs. Currently, this often occurs without considering all the factors that will influence the ultimate effectiveness of the system. The development of an overall detection system is complex and subject to multiple stringent requirements. In many cases, these requirements depend on a blend of human, technological, institutional, and other factors, including the need to filter out false alarms and to identify the legitimate transit of radionuclides. Development of new systems should also consider social and behavioral sciences aspects as they influence information and signal analysis constraints within a concept of operations. By using a multidisciplinary approach researchers at Texas A&M University in the engineering, math, social science and policy are creating a systems approach for evaluating a detection platforms prior to installation. At the conclusion of this project, DNDO will have a useful framework to determine a system's overall effectiveness prior to installation.

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2. Dorsey, Charlton: "Measured Energy Spectra of the $^{10}B(n,a)^{7}Li^{*}$ Recoil De-Excitation in Media of Different Density", Neutron Activation Analysis.

3. Gaukler, Li, Cannaday, Chirayath, Ding: "Detecting Nuclear Materials Smuggling: Using Radiography to Improve Container Inspection Policies", Available online 02 March 2010 DOI 10.1007/s10479-010-0717-y