INEEL/CON-03-00181
PREPRINT

Idaho National Engineering
and Environmental Laboratory

Active, Non-intrusive Inspection Technologies for Homeland Defense

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June 1, 2003 – June 5, 2003

Sixth International Meeting on Nuclear Applications of Accelerator Technology

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Abstract- *Active, non-intrusive inspection or interrogation technologies have been used for over 100 years - with the primary focus being radiographic imaging. During the last 50 years, various active interrogation systems have been investigated and most have revealed many unique and interesting capabilities and advantages that have already benefited the general public. Unfortunately, except for medical and specific industrial applications, these unique capabilities have not been widely adopted, largely due to the complexity of the technology, the overconfident reliance on passive detection systems to handle most challenges, and the unrealistic public concerns regarding radiation safety issues for a given active inspection deployment. The unique homeland security challenges facing the United States today are inviting more "out-of-the-box" solutions and are demanding the effective technological solutions that only active interrogation systems can provide. While revolutionary new solutions are always desired, these technology advancements are rare, and when found, usually take a long time to fully understand and implement for a given application. What's becoming more evident is that focusing on under-developed, but well-understood, active inspection technologies can provide many of the needed "out-of-the-box" solutions. This paper presents a brief historical overview of active interrogation. It identifies some of the major homeland defense challenges being confronted and the commercial and research technologies presently available and being pursued. Finally, the paper addresses the role of the Idaho National Engineering and Environmental Laboratory and its partner, the Idaho Accelerator Center at Idaho State University, in promoting and developing active inspection technologies for homeland defense.*

*Supported in part by the DOE Office of Nonproliferation Research and Engineering under Contract Number DE-AC07-99ID13727.

I. INTRODUCTION

Active, non-intrusive interrogation technologies are inspection systems that take advantage of an externally applied "source" to perform traditional imaging of, or to stimulate characteristic emissions from, an inspected object. While this broad definition covers a large range of inspection systems, this paper will focus only on ionizing radiation-based inspection systems using photons and/or neutrons for emission and/or attenuation measurements of the inspected object. These types of inspection systems are selected primarily due to their inherently high penetration capability of the source radiation with shielded configurations. While not intended to be all-inclusive, this paper will present representative systems that are being considered for homeland defense applications.

Despite today's public belief that active interrogation technologies are relatively new approaches being considered to address today's challenging homeland defense needs, active technologies have been in use for over 100 years. Röntgen[1] pioneered the first practical x-ray inspection application in 1895 as he was testing his cathode-ray tube prior to carrying out his first experiment. This single discovery marked the beginning of the atomic physics era and of many of today's contemporary medical applications with electrons and photons.

Jones, J.L., "Active, Non-intrusive Inspection Technologies for Homeland Defense*," Sixth International Meeting on Nuclear Applications of Accelerator Technology (AccApp'03)*, San Diego, CA, June 2003, pp. 33-41.

In the early 20th century, x-ray-based imaging continued to be rapidly developed, considerable research was being performed to understand electron, photon, and neutron interactions with matter[2], and interests in higher energy interactions were beginning. By the mid-20th century accelerator-based radiation sources were being developed, medical imaging was well accepted, and most common interactions with matter were well understood. During the last 50 years, considerable technological improvements have been made. With the advent of computers we are now predicting coupled photon-neutron interaction in materials,[3] are developing prototype and/or commercial systems for infield radiography and computed tomgography imaging,[4,5] are using higher energy systems for medical oncology applications,[6] are developing transportable systems for research and application use,[7] and are beginning to appreciate the technology implications and benefits of even higher accelerator energies.[8]

During the last several decades, government officials have acutely recognized the continued escalation of terrorism around the world (see Table 1); however, most were complacent in their perceived satisfaction of the existing level of homeland security and the fact that any *significant* event would not (could not) occur within the United States.

Table 1. Major Terrorism Events.

Event	**Year**	**Location**	**Explosive**
PanAm 103	1988	Lockerbie, Scotland	Semtex
WTC Bombing	1993	New York, NY	Ammonium Nitrate-based
Murrah Federal Building	1995	Oklahoma, OK	Ammonium Nitrate-based
Khobar Towers	1996	Saudia Arabia	C4
Embassy Bombings	1998	Nairobi, Kenja & Dar es Salaam, Tanzania	TNT
WTC, Pentagon	2001	NY, NY; Wash., D.C.	Airliner & fuel

After the September 11, 2001 terrorism events, officials have realized the consequences of this continued escalation and are now recognizing, accepting, and supporting the development of active inspection systems that allow significantly greater container content characterization within an approved radiation safety envelope.

Today homeland security demands our national and focused attention.[9,10] Specifically, the defense of our county mandates the efficient and successful detection of weapons of mass destruction (WMD) consisting of nuclear,[9] explosive,[10] and/or biological components within various shielded configurations and in various environments. These shielding configurations range from the simple package in a mailroom to the very complex 40-to-50-foot long, cargo containers passing through ports. The latter is receiving the most attention since there are over 301 port of entries in the US and over 16 million containers are brought into these ports annually.[11] Active interrogation technologies are presently addressing the detection of the nuclear and explosive components. The detection of shielded biological agents with a radiation-based active interrogation technique is still challenging at this time.

II. SOURCES AND EMISSIONS

Active inspection systems require an interrogating source of radiation and a means of detecting the characteristic object emissions. The radiation source emissions can be continuous or pulsed. This section will focus on sources and emissions applicable to homeland security.

Numerous photon sources are available. Photon sources include both gamma-ray (from atomic nucleus) and x-ray (from atomic structure) sources. Gamma-ray sources are radioactive sources such as Cs-137 (0.66 MeV) and Co-60 (1.17 and 1.33 MeV). X-ray (i.e., bremsstrahlung) sources provide a broad spectrum photon emissions from the interaction of energetic electrons with atomic electrons. The maximum energy of a bremsstrahlung spectrum corresponds to the maximum electron beam energy. Figure 1 presents representative bremsstrahlung spectra, for a given electron-photon converter, as a function of various electron beam energies.

Radioactive neutron sources include spontaneous fission sources (e.g., Pu-239, Cf-252 with energies up to 10 MeV with a most probable neutron energy of ~1.2 MeV) or alpha-n sources such as PuBe or

AmBe sources that provide significantly higher neutron energy emissions. Numerous reactions can also be used to generate a neutron source. Some of these reactions and their corresponding neutron yields are shown in Figures 2 and 3.

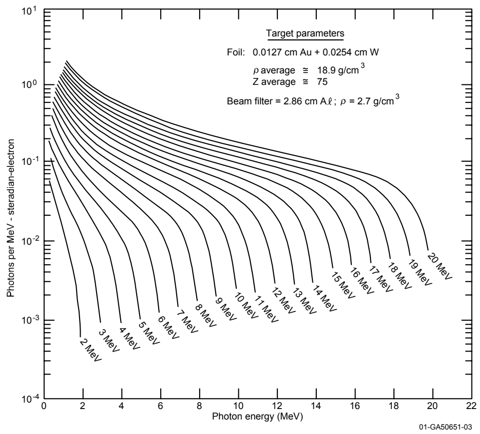

Figure 1. Bremsstrahlung radiation spectra.

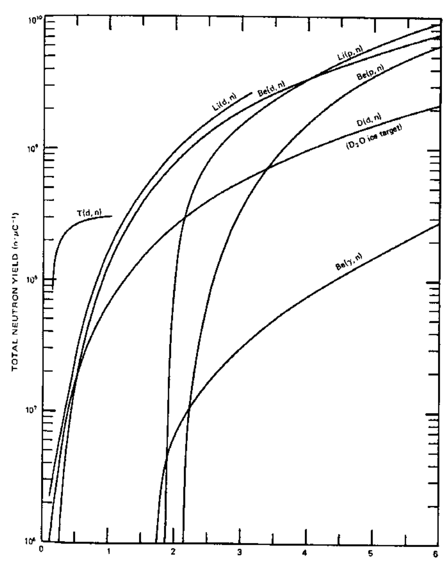

Figure 2. Neutron yield curve as a function of bombarding ion energy.[12]

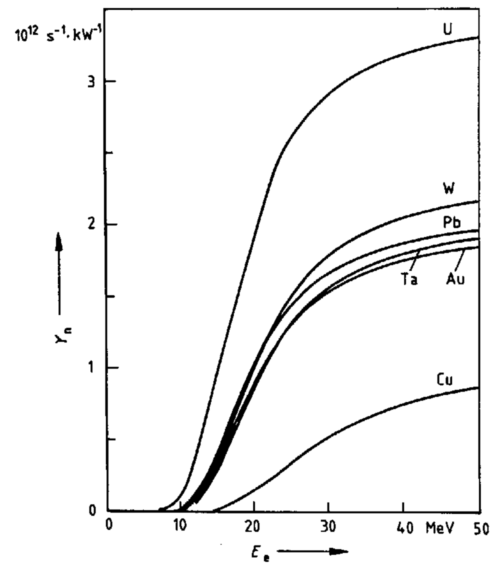

Figure 3. Photoneutron yields of infinitely thick metals as a function of electron energy.[13]

In general (d,n) reactions are the most prolific neutron producers (see Figure 4) with both the (p,n) and (γ,n) reactions following closely behind. In particular, the (γ,n) reactions can produce very high neutron fluence rates via high-power electron beams with neutron energies approaching the impinging electron beam energy less the threshold energy of the photonuclear process.

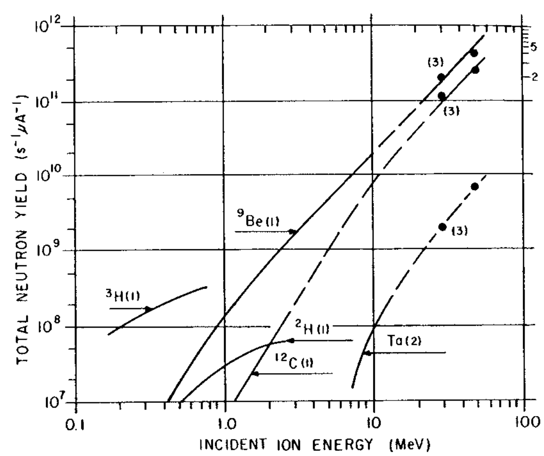

Figure 4. Neutron yield curves as a function of bombarding deuterium energy.[14]

Active interrogation applications for homeland defense involve the detection of characteristic photons and neutrons. For imaging applications, transmission and backscatter photons have been used by companies such as Science Applications

International Corporation, Inc. (SAIC), Advanced Research and Applications CORporation, Inc. (ARACOR), American Science and Engineering, Inc. (AS&E) and Varian Associates, Inc. These image detection systems are particularly sensitive to higher-Z, high-density objects. For lower-Z objects, neutron imaging continues to be considered. While direct neutron imaging with acceptable resolution is challenging, some interesting progress continues with thermal[15] and fast[16] neutron imaging.

Generally, the most specific information is obtained with elemental characteristic gamma-ray detection. In this spectral method, the interrogating neutrons interact with the object material(s) (via inelastic scattering or thermal neutron absorption) to emit gamma rays characteristic of the elements composing the material(s). The detection of these gamma rays is accomplished with one or more application-matched detectors. Representative detectors include sodium iodide (NaI), high purity germanium (HPGe), bismuth germanate (BGO), or cadmium-zinc-telluride (CdZnTe). When inelastic scattering is utilized, the detection method is typically referred to as a "fast neutron" analysis. When thermal neutron interactions are utilized, the analysis technique is called a Thermal Neutron Activation (TNA) analysis. For photon interrogation, the corresponding spectroscopic analysis is typically referred to as a Photonuclear Activation (PA) method.

III. IMAGING

Imaging is the most common and widely utilized active, non-intrusive inspection method. While the familiar medical/dental and handbag-type radiographic imaging uses less than 500 keV photons, homeland defense applications require both adequate image resolution and good inspected object penetration. This dual requirement drives the need for higher photon beam energies with performance-matched imaging detectors. Two of theses higher energy systems include the SAIC VACIS™ and the ARACOR Eagle™ systems.

The VACIS™ system[5] uses a gamma-ray source consisting of an ~1 Ci Cs-137 or Co-60 radioisotope, a steel and tungsten source housing, a tungsten slot shutter, and a motorized actuator for shutter rotation. Opposite to the source is a proprietary imaging detector assembly. The object to be imaged is positioned between the source and detector assembly. Currently, SAIC has developed six versions of the VACIS design to address various needs. Many of these systems are already in daily use worldwide. Figure 5 shows a mobile deployment.

Figure 5. Mobile VACIS™. (Courtesy of SAIC)

The ARACOR Eagle,™ shown in Figure 6, is a mobile, cargo inspection unit providing real-time, radiographic imaging of larger inspected items, such as a cargo container at a port The cargo image is acquired and displayed as the unit "drives over" the cargo container or other inspected item. The inspection system uses a nominal 6-MeV electron accelerator with a proprietary imaging assembly. Using a proprietary accelerator shield configuration, the Eagle operates within operational safe radiation exposure limits to its operators, the container, and any container stowaways. The inspection unit is designed to have a rapid port-to-port relocation capability. An Eagle™ unit is operational at the Port-of-Miami and additional units are being procured by U.S. Customs for other ports.

Figure 6. The ARACOR Eagle.™ (Courtesy of ARACOR)

IV. EXPLOSIVE DETECTION

As has been identified in Table 1, explosives appear to be the weapon-of-choice for many terrorists. While the detection of explosives (pound quantity) has been, and continues to be, the focus of the Transportation Security Agency relative to handbags, luggage and personnel, another challenging detection is being investigated by the Department of Defense (DoD) for vehicles entering facilities, such as military bases. The DoD's Physical Security Equipment Action Group (PSEAG) has identified[10] the need for detecting large quantities of concealed explosives in a car or truck from a stand-off distance of several meters. This group believes that neutron-based technologies should be able to meet this objective within 18 months. Four explosive detection technologies are presented below.

The Pulsed Elemental Analysis with Neutrons (PELAN) system[17], shown in Figure 7, is a mobile, SAIC-patented, explosive and illicit drug detection system developed at Western Kentucky University between 1998-2001. PELAN uses as a pulsed, 14-MeV neutron generator with a combined pulsed fast/thermal neutron activation method to detect and measure characteristic gamma rays from the major and minor chemical elements in an object. PELAN uses BGO or gadolinium orthosilicate (GSO) gamma-ray detectors. Explosives and illicit drugs are identified primarily from ratios of chemical elements such as H, C, N, and O, the major elemental constituents of them.

Figure 7. The PELAN™ System. (Courtesy of SAIC)

The ANCORE Vehicle Explosive Detection system (VEDS) is a TNA technology capable of detecting explosives in cars and trucks. Two VEDS configurations are available: a portal and a mobile version. Figure 8 shows the portal VEDS system. In the portal system the VEDS is rail-mounted and moves relative to a stationary inspected vehicle. In the mobile version, VEDS is mounted on a vehicle and driven along side the inspected vehicle. The nominal system uses a Cf-252 neutron source and an array of co-located NaI detectors. A modified design is being developed which replaces the radioactive source with a neutron generator.

Figure 8. The portal VEDS system.

The ANCORE Cargo Inspector (ACI), shown in Figure 9 uses the Pulsed Fast Neutron Activation (PFNA) technology.[18] The system can detect explosives, narcotics, alcoholic beverages, chemical agents, etc. The principles of the PFNA method are presented in Figure 10. PFNA uses a directed, pulsed beam of high-energy neutrons that interact in

Figure 9. ANCORE ACI system.

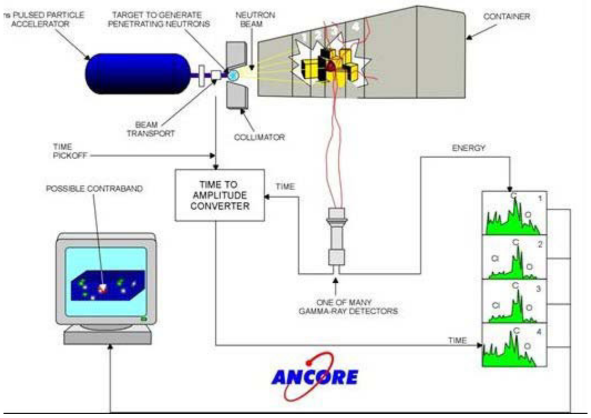

Figure 10. Principles of PFNA operation. (Courtesy of ANCORE).

the nuclei of elements in scanned objects. The directed neutron beam is rastered over the scanned object during the inspection. The element-characteristic gamma rays are detected and analyzed. Inspections are safe to the user, to the cargo, and to stowaways.

The Pulsed Photoneutorn Activation (PPA) system[19] shown schematically in Figure 11, is a TNA-based system using a pulsed, high-energy (up to 12-MeV) electron accelerator and a custom-built HPGe gamma-ray spectroscopy system designed especially to operate within intense pulsed photon environments. This system was designed and built by the Idaho National Engineering and Environmental Laboratory (INEEL). Each electron pulse produces highly penetrating bremsstrahlung photons that can also be used to provide radiographic imaging. The interrogating source neutrons are generated by the bremsstrahlung photons interacting in a photoneutron source material co-located with the photon source.

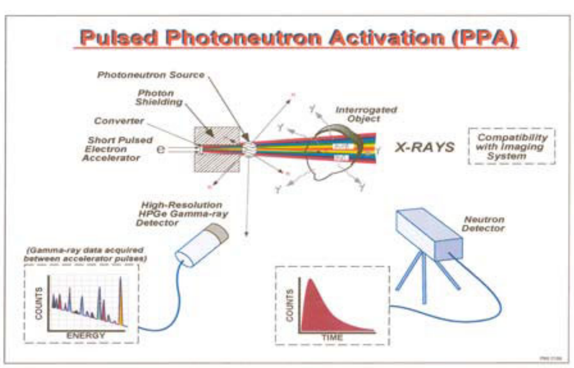

Figure 11. Schematic of the INEEL PPA system.

The interrogating neutrons induce element characteristic gamma rays from the interrogated object. The PPA system was successfully demonstrated to the PESAG on October 2002 and clearly showed at least a 3-m explosive detection of explosives located within the trunk of a vehicle.[20]

The Portable Isotopic Neutron Spectroscopy (PINS) system[21] is a TNA-type, nondestructive tool designed to identify the contents of munitions and chemical storage containers. The nominal PINS system, shown in Figure 12, uses a Cf-252 source and a HPGe detector. The system was designed and built at the INEEL, has been commercialized, and has had considerable utilization with the U.S. Army. A neutron generator version of the PINS has also been developed. The PINS system, like the PPA system, has also been shown to effectively detect explosives concealed in cars.[20]

Figure 12. The INEEL PINS system.

V. NUCLEAR MATERIAL DETECTION

Before the September 11, 2001 terrorist events, most nuclear material detection efforts within the US focused on material safeguards and waste management issues.[22] Over the past decade nearly 400 international cases of purported nuclear smuggling has been complied by the International Atomic Energy Agency.[11] Within the US, safeguard applications focused primarily on inventory control and the ability to detect relatively small amounts of diverted material on personnel via portal monitors at entry and exit choke points. For waste management applications, 55-gallon drums and crate-like configurations were of interest. Similar to cargo container inspections, the waste management applications required nuclear material detection within a broad range of non-nuclear material contents.

To address the waste management applications, systems like the Los Alamos National Laboratory's (LANL) Crate Waste Assay Monitor (CWAM),[23] shown in Figure 13, have been developed. These systems consist of a neutron generator and a large-solid angle configuration of neutron detectors (typically composed of helium-3 gas) around the inspected object. Pulsed neutrons interrogate the object and induce subsequent fissions in the nuclear material. By time correlating the neutron emissions with each interrogation pulse, the detection response can identify differences that directly indicate information about the nuclear material within the contents. This inspection method is also applied to smaller packages.

Figure 13. Crate Waste Assay Monitor (CWAM) (Courtesy of LANL)

Another representative detection system indicating an ability to detect nuclear devices within cargo containers is the ANCORE's PFNA technology.[24] This technology was presented in Section IV.

The final technology being developed to address nuclear material detection within cargo containers is the INEEL Pulsed Photoneutron Assessment Technology (PPAT)[25,26]. This technology uses high penetration capability of energetic photons (up to 12 MeV) from a pulsed, linear electron accelerator to induce fissions in nuclear materials. The resulting delayed neutron emissions are measured between each accelerator pulse to detect the nuclear material contents, and variations in the electron beam energy can allow nuclear material identification. As shown in Figure 14, efforts are currently underway to incorporate the PPAT detection system with the ARACOR Eagle™ design to support combined radiation-safe, nuclear material detection with real-time radiographic container imaging.

Figure 14. ARACOR Eagle™ with PPAT Detection System.

VI. INEEL's ROLE

From the early waste management applications to today's homeland security needs, the INEEL has been and continues to be a nuclear science leader in non-intrusive, active interrogation technology development. INEEL's strong partnership with the Idaho Accelerator Center (IAC) (see Figure 15) at the Idaho State University, has effectively merged academic strength with national laboratory capability to provide a nationally recognized, very flexible environment for performing research, development, and testing of active systems.

Figure 15. The Idaho Accelerator Center.

Today's INEEL's active interrogation thrust involves the fundamental research and development of non-intrusive, standoff, cargo container inspections. Current research is directed toward the detection of nuclear smuggling, especially very-difficult-to-detect Highly Enriched Uranium (HEU), and explosives within cars, railcars, trucks, and cargo containers. Evolving research and development will incorporate other WMD interests, will enable enhanced applications with higher beam energy operations, will provide a more comprehensive and in-depth understanding and evaluation for greater standoff distance interrogation applications, will investigate smaller quantities of nuclear material detection, and will support adversarial analyses for various threat scenarios.

To achieve these research and development objectives, the INEEL and its research partners will develop and demonstrate advanced capabilities and techniques that provide for robust "cabinet-safe" (i.e., radiation safe) designs with optimized/customized interrogation system detection and imaging components. These systems will provide greater resolution and fidelity for car, truck, and cargo container characterization and identification with reduced overall inspection times.

These enhanced inspection systems will be validated and demonstrated utilizing indoor and outdoor challenge testing environments and full-scale transportation system scenario mockups. It is planned that within five years, INEEL will develop a Center for Non-intrusive, Active Interrogation Research and Applications (CNAIRA) that will significantly advance the state-of-the-art in active interrogation inspection systems. These active systems will provide unique operational capabilities with and without "cabinet safe" operations and integrate various complementary activation techniques, sensors, detectors and imaging capabilities to support various commercial and national security needs. Where unique capabilities, such as research and facilities, already exist to support specific research and development needs, CNAIRA will coordinate activities to assure maximum synergism and timely technology development and deployment.

III. SUMMARY

This paper addresses the renewed interest and utilization of active interrogation technologies to meet today's national homeland security needs. The paper provides a brief historical overview of active interrogation, highlights some of the more popular active technologies being used or developed for homeland defense, and finally, presents the INEEL's continuing and future roles supporting our national homeland defense mission.

ACKNOWLEDGMENTS

The author would like to acknowledge contributions from ANCORE, ARACOR, SAIC, LANL, and the Idaho Accelerator Center in the preparation of this work. I would also like to thank the support of the Department of Energy (DOE) Office of Nonproliferation Research and Engineering and the Department of Homeland Security. The work was performed under DOE Idaho Operations Office Contract DE-AC07-99ID13727.

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