Technology Sector – Security

Sub Sector – Detection

Segment - Radiological and Nuclear Weapons

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1. Title

Detection of Radiological and nuclear weapons

Keywords: alpha particles, beta rays, gamma rays, high energy photons, high energy electrons, radiation monitoring, plastic scintillators, pure crystal scintillators, solid state devices, nuclear resonance fluorescence, nanophosphor, nanocomposite

2. Definition of Technology Segment

Nuclear weapons and radiological dispersal devices illegitimately smuggled across the European borders present a significant threat to civilian population. Radiological dispersal devices (also know as ‘dirty bombs’) are capable of dispersing highly radioactive particles over large densely populated areas. Alpha particles (equivalent of a helium nucleus), beta rays (high energy electrons) and gamma rays (high energy photons) are detected by devices to warn of the presence of a nuclear weapon or radiological dispersive device [1].

3. Short Description

International smuggling of weapons grade nuclear material presents a significant security challenge. Between 1993 and 2004, the International Atomic Energy Agency has reported 18 incidents that related to smuggling of weapons grade nuclear materials. The proliferation of nuclear weapons can take place through the borders at ports, airports, road passengers and through the postal system. A tactical or improvised nuclear weapon would be small enough to be transported in modular containers. It was reported that 25 kilograms of highly enriched uranium or 4 kilograms of plutonium-239 would be adequate for a nuclear explosive device. A significant challenge is presented by dirty bombs, which would present a significant challenge to health of civilians. Americum-241, californium-252, cesium–137, cobalt-60, iridium–192, and strontium-90 are radioactive species that could possibly be used for a dirty bomb. The radioactive isotopes californium-252 and americium–241, are used in the oil industry and smoke detectors respectively, therefore are easy to obtain for a dirty bomb [2]. Weapon grade plutonium and highly enriched uranium can also be used for radiological dispersal devices. Radiological dispersal devices can thus contain a variety of radioactive species that emit gamma rays, neutrons and/or bremsstrahlung radiation.

Radiation monitoring is largely done by detecting gamma rays emitted by radioactive materials. The gamma rays cover a spectrum of energies. Gamma rays passing through matter deposit a part of their energy resulting in electrons that can be detected. One method of detection of photons in a detector is a process called scintillation. Plastic scintillators, pure crystal scintillators, and solid state devices are used for detecting gamma radiation. The drawback of plastic scintillators is the low energy absorption due to the low density of the material. As a result the instruments using such detectors cannot identify the radioactive material accurately. Pure crystal scintillators and solid state devices are relatively better at absorbing all the energy of gamma rays due to their higher density and atomic number. Radioactive isotopes such as strontium-90 emit beta rays, which when shielded produce bremsstrahlung radiation which can be detected by the same methods as gamma rays. Weapon grade plutonium and highly enriched uranium are relatively less radioactive with respect to gamma ray emission in comparison to other isotopes, therefore making them more difficult to detect. Neutrons are also emitted by weapon grade plutonium, often making detection easier due to the low natural background from cosmic radiation. The neutron detectors function by detection of protons released from nuclei struck by neutrons, of fission daughters or by measuring gamma rays, electrons and other charged particles. Uranium isotopes emit alpha particles and gamma rays, and not as many neutrons [2].

A number of strategic tools are used in the detection of radiation such as radiation portal monitoring equipment, personal radiation detectors, hand held detectors and x-rays systems for imaging of shielding. Radiation detection systems can be passive or active. Passive systems for detection of radiation include radiation portal monitoring equipment, mobile systems, hand held, backpack and belt monitoring systems, all of which have been deployed. Mobile x-ray and fixed systems have been used for penetration of cargo containers for suspected cargo. Plutonium and a few other radioactive materials emit neutron and tus neutrons are of particular interest in detection applications at border crossing [3].

Radiation portal monitoring equipment has been deployed for border crossing and port application in detection of illicit nuclear material. Detectors of gamma rays based on polyvinyltoluene (PVT) and thallium doped crystalline sodium iodide have been demonstrated and deployed. For passive screening of gamma rays, the energy range of interest for detection was between 20 keV to 3 MeV [4]. A comparison of radiation portal monitoring equipment for border security was done using gamma ray and neutron detectors. A comparison of polyvinyltoluene and thallium doped crystalline sodium iodide for vehicle based radiation portal monitoring has also been evaluated in the literature. The spectral capability of NaI(Tl) is superior to PVT for isotopic identification, though the cost of NaI(Tl) has been reported to be much higher than PVT. A range of environmental and operational factors determine the suitability of a detector in different operating scenarios. Each detector type offers some advantages for various operating conditions of portal monitoring systems [5].

Energy based alarm algorithms with enhanced sensitivity over gross counting have been implemented for radiation portal monitoring equipment. The energy information obtained from plastic scintillators can be used to distinguish between naturally occurring radioactive material and special nuclear material. The energy based algorithm was considered to be a much desired improvement in detection over gross count algorithms. One of the main limitations of radioaction portal monitoring systems is the presence of naturally occurring radioactive isotopes that can present a significant operational challenge [3,6].

Nuclear weapons detection in transportation cargo has been demonstrated with a range of techniques, including both passive and active detection. The photo-fission of neutron emission induced by gamma rays forms the basis of one active detection approach. The technique and its effectiveness has been demonstrated for radioactive material in simulated shipping containers and air-cargo [7]. Detection of nuclear weapons in cargo has been demonstrated using a pulsed beam of neutrons, that produce fission events and detection of their fissionable material is done from the beta delayed neutron emission or beta delayed high-energy gamma radiation. This is another of the several active interrogation detection methods, and has been demonstrated for simulated shipping cargo [8].

Nuclear Resonance fluorescence, another potential active interrogation technique, has been demonstrated in the detection of isotopes of uranium in a laboratory. The basis of the method is a unique signal that is relevant to each nuclei. The technique combined with effective algorithms has been demonstrated in the laboratory as a possible method that may be applicable to detection of material in sea containers, truck containers, trucks and other vehicles [9].

Monitoring of radioactive xenon in air has been used to detect nuclear weapons explosions as part of the worldwide network of the Comprehensive Test Ban Treaty verification effort. A prototype single phoswich detector has been used to detect beta particles and gamma rays from radioxenon isotopes [10].High resolution inductively coupled plasma mass spectrometry and accelerator mass spectrometry have been demonstrated in detecting ultra low level of uranium isotopes in marine environments. The uranium isotope signature provides valuable information on origin of uranium. The method has useful applications in monitoring radioactivity in depleted uranium environments and undeclared nuclear activity or movement of nuclear material [11].

Detection of radioisotopes using a distributed sensor network, as opposed to central fixed systems, has been proposed and developed. These distributed sensor network, coupled with a monitoring portal has been demonstrated. The sensor array consisted of sodium iodide scintillators that were connected to a platform for processing of gamma counts. The performance of the array was reported to be higher than that of a single detector, though that is a controversial claim. The advantage of this proof of concept is that it may be inexpensive, further research is aimed at increasing sensitivity and developing an integrated platform for chemical and biological weapons [1].

The use of various detectors for radioactive species has been mentioned earlier. A system for simultaneous detection of radiation species such as x-rays, gamma rays, neutrons and minimum ionising particles has been observed in the literature. The sensitivity of the scintillators in the research was achieved using nano-sized particles, dopants and extruded plastic material. Three different type of detectors have been described, which identify specie of radiation. Nano-sized particles of lithium have been used in neutron detectors. The wavelength shifting fibre absorbs scintillator light at a wavelength and re-emitting it at a higher wavelength to better match the photodetector used [12].

The use of nanoscale materials for detection of radiation is expected to overcome single crystal based detectors limitations such as size and cooling requirements to very low temperatures. Nanophosphor has been mentioned as a candidate material for scintillators and detectors. Cerium doped lanthanum halides (less than 10nm in diameter) have also been mentioned as suitable candidates for scintillators nanocomposites. Due to their brightness and short decay lifetime they are very effective in gamma ray detection. Scaling up of the synthesis of cerium lanthanum fluoride to kilogram quantities remains a further research challenge that remains to be addressed [13].

Enhanced optical properties of nanocomposites made of existing scintillator materials have been reported in the literature. The nanocomposites offer enhanced light output, decreased costs and scalability have been demonstrated at the proof of principle stage. Cerium doped lanthanum fluoride has been synthesized, nanoparticles having a size of 25 -100 nm, have shown a three times increase in light intensity as compared to bulk material used for scintillation. Further research in the area was identified as synthesis of nanophosphors as scintillators and their fabrication as nanocomposites. Measurement of absolute light yield and linearity of the nanocomposite were mentioned as challenges for characterization [14].

Solid state semiconductor detectors offer advantages over gas filled detectors and scintillator detectors due to excellent energy resolution and higher efficiency. High purity germanium detectors are the gold standard for gamma ray detection but require cryogenic temperatures. A number of semiconductors have been suggested for application such as cadmium zinc telluride (CZT), cadmium telluride, gallium arsenide, indium phosphide, mercury iodide and thallium bromide. CZT offer advantages due to its wide band gap, high resistivity and commercial availability. The higher resistivity is a desirable characteristic as it decreases noise level thus improving the resolution of detection. A synthesis process for producing nanowire arrays of CZT has been mentioned in the literature for detecting gamma ray radiation. In the process CZT was electrodeposited on a titanium dioxide nanotubular template. Stacks of CZTs with very high resistivity were fabricated and connected. It was experimentally demonstrated that the flow in the current increased when exposed to a radiation source. The potential of nanowires being used as a radiation detector at room temperature was at a much lower bias applied in relation to bulk material detectors. Very high sensitivity to radiation was experimentally demonstrated [15].

Other recent methods have been mentioned in the literature such as the Neutron Imaging Camera for detection of weapon grade plutonium at borders. The camera is based on three dimensional image tracker developed initially for applications in gamma ray astrophysics. The working principle is based on measuring the energy and position in three dimensions of the charged particles moving through the camera medium. The application was successful

demonstrated to identify radiation at stand-off distances and in the presence of other background emissions [16]. An Electronic Neutron Dosimeter has been mentioned in the literature for detecting radiation. It uses scintillators on a pair of photomultiplier tube minimizing the power consumption and increasing operational times. The dosimeter has been prototyped with results exceeding electronic neutron dosimeter standards [17].
Microcantilevers were reported to detect an alpha particle as it impinges on an electrically insulated metallic surface by undergoing a deflection of a few nanometres. The particle is detected by a shift in the resonance frequency due to electrostatic forces. A single alpha particle can be detected using this method, however other conventional methods have been shown to have higher sensitivity as compared to these detectors [18].

One of the main challenges of detecting these threat radioactive materials is the shielding using lead and other dense materials for gamma rays, and hydrogenous materials for neutrons. An additional challenge is interference from medical isotopes and other slightly radioactive, but relatively innocuous materials such as smoke detectors, fertilizers, television sets, abrasives and glazed ceramics. The approach of using X-ray scanners has been used in the United States, for any shielding that may be used to hide radiological weapons. Other methods such as active interrogations using gamma ray and neutrons have also been reported. As mentioned above, these induce fission in uranium and plutonium, resulting in gamma rays and neutrons that are detected [2].

4. State of Research and Development

The sections give an overview of the technology development in relation to a specific technology. Fundamental Research is defined for this purpose as research with no particular goals of commercialisation. Applied Research is defined as research conducted in academia and industry directed towards a specific purpose and application. Prototype has been defined as Applied Research or Fundamental Research that has found a potential market application. Technologies that are in the field trial state are defined as those that are in the process of commercialisation, and are being tested. Deployed nanotechnologies are those that have found an early stage market. Mass Market has been defined as those technologies that have been adopted by large population and are attractive high growth markets. The technologies have been mentioned are those mentioned in the literature review for nuclear and radiological weapons detection. The scale of readiness mentioned ranges from fundamental research to mass market. The range of activity indicates various methods and materials being used at different stages of readiness. The table RNW.1 below gives an overview of enabling technologies for detection of radiological disperse device and nuclear weapons in relation to their development status.

Table RNW.1 - Technology and its Development Status for radiological disperse devices and nuclear weapons detection

	Fundamental Research	Applied Research	Prototype	Field Trials / Pilot plant (Pre-commercialisation)	Deployed (Commercialised)	Mass Market
Radiation portal monitoring		▪	▪	▪	▪	
Sensor Array		▪	▪	▪		

Spectrometric method			▪	▪	▪	
Nuclear Resonance fluroescence		▪				
Nanomateri-al based Detectors		▪	▪			

5. Additional demand for research

Specific research needs were mentioned in the literature relating to different detection aspects are as follows:

- Materials research needs for CBRNE sensors has been identified as developing sensors with the ability to detect and warn. Sensor capabilities to allow functionality at stand off distances in order to protect personnel in conflict situations. Enhanced understanding of the energetic behaviour of weapons and its packaging modes has been suggested. Enhanced and portable imaging techniques have been identified as a research need for civilian areas with high shipping container traffic. Integration of imaging and detection techniques with mass transportation has also been mentioned [19].

6. Applications and Perspectives

In the expert engagement process for the technology segment, the following perspectives were observed:

- Funding research and development for detection of CBRNE and Narcotics was considered very important for society and economy of Europe.

- The most important drivers for research and development of '*detection of CBRNE and Narcotics'* were considered technological and social impact. The technological drivers relate to cost, performance, efficiency and absence of solutions. Other secondary drivers were indicated as operational advantage in conflict situations, safety, productivity gains and regional security policy.

- The main drivers for R&D of *'radiological and nuclear detection'* were mentioned to be 'mobility of detection unit', 'cost of sensors, devices and instruments', and 'accuracy of detection'. Other secondary drivers were 'time for detection', 'integration of detection platform', and 'life time of operation'

- The main barriers to research and development of *'detection of CBRNE and Narcotics'* were mentioned as 'availability of finance to early stage companies' and 'inadequate technology transfer from Universities'. Secondary barriers indicated were 'intellectual property conflicts', 'lack of tax incentives' and 'lack of supportive government policy'.

- Qualitative responses indicated to meet the challenges of 'availability of finance', EU needs to consider dual commercial use of security technology as the market was relatively smaller than US. While trends in US are towards government driven technology that is validated, EU grants are inadequate for proving technology. It was suggested that government validation of systems was necessary as laboratory systems not scaled for field use.

- The main barriers to R&D of *'radiological and nuclear detection'* were indicated as 'lack of equipment and testing facility', and 'limited supporting policies'. Other secondary barriers were indicated as 'lack of reproducible results', 'failure in integrating devices' and 'robustness of field trials'.

- Qualitative responses suggested the different approach towards funding research in radiological and nuclear weapons from different agencies. Short term 2-3 year view was detrimental to research efforts.

- The desirable characteristic of a radiological nuclear detector was mentioned inexpensive, excellent energy resolution, thermally stable, physically robust, and usable for a long operating life.

- The application trends were mentioned as:

    - Radiological and nuclear detectors are physically large. Physical miniaturisation is not possible therefore improved material performance is being investigated.

    - Increased energy analysis for radiation detection has led to higher costs. The direction of research is towards extracting more information from less expensive technological solution.

    - Response time was entirely application dependent. While in border situation 2-3 seconds response time is ideal, longer at trading ports, it should be within milliseconds in crowded locations.

    - Operational factors important in radiological- nuclear detection are time, distance and shielding. Time of detection is for seconds, and distance is based on packages and physical sizes of vehicles. Shielding is considered to be the main factor for planning against different scenarios.

    - Results from technique such as Nuclear Resonance fluorescence were considered poor for laboratory condition. In real situations with shielding they may not produce predictable results like those from active induced fission by neutrons or gamma rays.

    - One of the main application problems was considered to be absence of an accelerator which can address the lack of tunable, variable energy, continuous source of gamma rays with the right energy. The present sources are pulsed thus resulting signal to noise ratio are not feasible for application of technique.

    - CeF_3 material was mentioned to have been developed as proof of principle. The limitation for CeF3 was reiterated to result from the low light output. It was mentioned that scale up to 500 gram/batch synthesis of CeF_3 had been achieved.

    - There are limitations in understanding of the production process.

    - All detector materials show limitations and advantages over each other.

    - Application areas where nanomaterials can add value would be nanoparticle inclusion in plastic for plastic scintillators.

    - Nano-additives could play a role in gamma radiation detectors

    - Nanotechnology could enhance light detection system for photo tube detection and gas detectors.

- The sensing methods for radiation and nuclear weapons detection that are presently deployed are radiation portal monitoring and spectroscopy.

- Methods for radiological and nuclear detection that are expected to be deployed after at least 5 years of development are sensor arrays for radiation detection and nanomaterials based detectors.

- The factors determining uptake of radiation detection technology are physical size, price, robustness, resolution. Response time, count rate (some scintillators are slower than others), and relationship to material properties.

- The moderately attractive future growth markets for explosives detection were expected to be radiation portal monitoring, sensor arrays for radiation and spectroscopy methods.

- Investment in technology and evaluation of product markets is important for radiation detection. One company holding sole monopoly in a market through patents is counterproductive for development in security.

- Basic research for radiation detection was perceived to be better in Europe than North America, mainly concentrated in Universities. National laboratories in US were focused on technology development and transfer for radiation detection. Europe was considered particularly weak for technology transfer.

The theme of integrated platform for detection of chemical, biological, explosive, radiological and nuclear threats was conducted at Dusseldorf in March 2009. The following outcome and recommendations resulted from the discussion:

- Technology was not sufficiently advanced to achieve single platform detection.

- An integrated modular system that focuses on Chemical, Biological and Explosive as one unit and Radiological-Nuclear detection as a separate module is a better approach.

- One of the main weaknesses for CBRNE detection was considered to be systems integration. It was suggested that a statement of requirements to be produced taking nanotechnology into consideration.

- Accuracy and reliability of measurement was considered to be most important characteristic. Reproducibility of measurements and operating life of sensor were considered to be poor for modular systems of detection.

- The cost of false positives are very high, therefore operational definition should be developed on a case by case basis for a modular system.

- The need for greater fundamental research in understanding the sensing mechanism was emphasised.

- It was recommended that communication between materials and sensing community be improved in order to create mutual awareness of technical breakthroughs.

- The first area of application is expected to be transportation hub for such a modular system.

- Technology penetration and application driven by state regulation for CBRNE detection.

7. Current Situation within EU

The following Preparatory Action for Security Research Funded projects were funded by the European Commission and are relevant to radiation and nuclear detection:

- European Security: High level study on threats responses and relevant technologies (ESSTRT). The support action project has provided a comprehensive overview of necessary responses to security challenges. These include technologies for detecting nuclear weapons and radiological disperse devices at airports and travel hubs. The project also investigated technologies that could develop smart containers, and border security against weapons [20].

- CBRNE related testing and certification facilities - a networking strategy to strengthen cooperation and knowledge exchange within Europe (CREATIF) was initiated early in 2009. The project aims to create a network of product testing facilities for CBRNE detection [21].

The following framework 7 projects funded under the security theme by the European Commission have relevance to the radiological-nuclear detection.

- Cooperation across Europe for Cd(Zn)Te based security instruments (COCAE) project initiated in 2008 is focused on spectroscopic measurements for detecting radioactivity using Cd(Zn)Te crystals [22].

- Integrated mobile security kit (IMSK) was initiated in 2008. The objective of the project is to combine technology solutions from Detection of CBRNE, area surveillance, and check point control for additional sensitive security locations. The sensor data is expected to be integrated with communication and data module to a command centre [23].

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