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Detecting nuclear and radiological materials

Summary

On 10-11 December 2007 the Royal Society held a two day workshop to explore innovative approaches for detecting the illicit trafficking of nuclear and radiological materials. It began by setting out the potential threats of concern and reviewed current detection capabilities that address them. It then explored novel approaches to improving these capabilities, and considered ways to develop any promising ideas. The workshop incorporated a limited discussion of nuclear forensics. It brought together 70 leading scientific and policy experts from the UK, USA, Russia, Israel and several other European countries. This report summarises the key issues raised in the presentations and discussions. It represents views expressed at the workshop and does not necessarily represent the views of the Royal Society. A programme and list of participants are provided in Appendices A and B respectively.

The key points arising from the workshop were:

- The detection of nuclear and radiological materials is one facet of a multilayered defence against nuclear security threats, which also requires robust prevention and response elements. Information sharing, especially of good intelligence, is central to all aspects.

- In the near term (3-5 years) low cost detectors with improved energy resolution for gamma ray spectroscopy will remain the key priority. Germanium based detector technologies remain the gold standard and developments in cooling will improve and broaden their field applications. In the medium term (5-10 years), there are promising opportunities to develop new technologies, such as muon detection systems. In the long term (10-20 years) detection could benefit from advances in nanotechnology and organic semiconductors.

- Systems analysis underpinned by powerful information technologies should inform detector design and increase overall system effectiveness. Simulations are essential for optimising the performance and deployment of different detectors. They can identify vulnerabilities and thereby help focus the allocation of resources. Networking detector technologies is an important part of this approach.

- Aerial detection systems are valuable in preventative and responsive roles. Unmanned aerial vehicle based systems show particular promise for emergency response and highly manoeuvrable rotary-wing systems are valuable in urban environments.

- Nuclear forensics capabilities need to be improved as reliable attribution leading to prosecution presents a strong preventative deterrent to potential traffickers. For robust and rapid attribution of radiological and nuclear materials the fusion of different technical and intelligence data is important, including sharing of international material databases.

- International cooperation is essential to develop shared threat assessments to help identify and prioritise capability gaps. Greater coordination is needed at all levels for research and development, certification, testing, and trialling of detection systems, as well as technology sharing and training. This will help reduce funding costs, avoid duplication of efforts, and build confidence in global nuclear security.

Contents

1 Detection in context

1.1 Nuclear security

Robust nuclear security requires the prevention of, detection of, and response to, theft, sabotage, unauthorised access, illegal transfer or other malicious acts involving nuclear and radiological material and their associated facilities. Continued reports of illicit trafficking in nuclear and other radioactive material demonstrate the need for States to address their nuclear security. The International Atomic Energy Agency (IAEA) manages an illicit trafficking database (ITDB) that relies on member States voluntarily reporting confirmed cases of trafficking. Following the first seizures of nuclear material in 1991, reported incidences of illicit trafficking reached their height in the mid-1990s. Since the 1990s, there have been relatively few confirmed incidents of illicit trafficking in *nuclear* material, such as uranium and plutonium, but there have been significant increases in both the numbers of confirmed incidents of illicit trafficking in *radiological* material, such as caesium and cobalt, and confirmed incidents of lost or stolen radiological material that have not been recovered.

Nuclear security must also adapt to the potential threat of nuclear terrorism, especially since the possibility of suicide terrorism means that radioactive material can no longer be assumed to be self-protecting. Potential nuclear terrorism threat scenarios include:

- acquisition of a nuclear explosive device, such as a nuclear weapon;
- acquisition of nuclear material to build an improvised nuclear explosive device;
- acquisition of radioactive material to construct a radiological dispersal device;
- sabotage of installations, locations or transports involving radioactive material.

To combat these potential threats, a multi layered defence that includes robust prevention, detection, and response elements is needed. Information sharing, especially good intelligence, is central to all these stages. The highest priority, due to the very high consequences of an incident, is detecting special nuclear materials (SNM), such as highly enriched uranium and weapons grade plutonium, and so efforts should be focused in this area. Improvements relevant to detecting SNM will usually also improve capabilities to detect other radiological material.

1.2 Prevention

Prevention provides the first line of defence. It involves the physical protection, accountancy and control of nuclear and radiological materials. It also includes the overall reduction of SNM and nuclear weapons. The IAEA's nuclear security activities are underpinned by a number of international binding and non-binding legal instruments, such as the Convention on the Physical Protection of Nuclear Material; the Convention on the Suppression of Acts of Nuclear Terrorism; the various Non-Proliferation Treaty, safeguards agreements and Additional Protocols; United Nations Security Council Resolutions 1540 and 1373; and the voluntary Code of Conduct on the Safety and Security of Radioactive Sources. Universal ratification and implementation of these instruments is vital to prevent nuclear incidents and nurture a new international culture of nuclear security. Preventative measures provide increased timeliness and leverage for responding to nuclear security threats.

1.3 Detection

Detection provides the second line of defence. It involves screening for nuclear and radiological materials at the exits of nuclear facilities, borders, ports, and airports, as well as in transit. Measures used at this stage include: detectors of various types, such as radiation portal monitors (RPMs) at ports and borders, in-situ detectors within transport containers, distributed networks and wide area searches; passive radiation monitoring and/or active interrogation of SNM; and inspection and unpacking of cargo.

1.4 Response

Response provides the third line of defence and concerns the ability to respond to a nuclear or radiological incident and mitigate the adverse effects. This incorporates the use of nuclear forensic investigations to determine the nature and source of the threat material.

1.5 US and UK nuclear security efforts

Established in 2005, the US Department of Homeland Security's Domestic Nuclear Detection Office (DNDO) is developing a global nuclear detection architecture to provide a multilayered defence to detect and interdict the illicit trafficking of radiological and nuclear materials into the USA. The DNDO and US Customs and Border Protection (CBP) are deploying radiation portal monitors (RPMs) at seaports and land border crossings, acquiring experience for future deployments as more capable RPMs are developed. As part of the Secure Freight Initiative, Advanced Spectroscopic Portal (ASP) systems have been installed alongside existing RPMs at several foreign ports, including Southampton in the UK, to scan containers before they depart for the USA. In collaboration with CBP and the US Coast Guard, DNDO is establishing a National Small Vessel Security Strategy to address the problem of smuggling material by non-container means, such as small boats. DNDO is also testing initial deployment concepts at airports with a focus on the last point of departure, and considering how to screen aircraft upon arrival. Current efforts focus on data collection for radiological backgrounds and signatures for various airframes, site surveys at domestic airports, and pilot deployment of detectors at selected airports.

DNDO aims to establish protocols for correct responses to incidents, such as radiological material going missing, an RPM raising an alarm at a border crossing or an emergency situation. Basic response preparedness is needed for any location, not just for established nuclear facilities and industrial sites. In all cases, material seized at the scene needs to be correctly registered, stored and transported for forensic investigation and attribution to enable possible prosecution. DNDO is setting up a National Technical Nuclear Forensics Centre to provide centralised planning and integration of US Government nuclear forensics programmes.

Established in 2007, the Office for Security and Counter Terrorism within the Home Office is responsible for implementing the UK Government's multi layered counter terrorism strategy (CONTEST). As regards nuclear security, CONTEST aims to improve the physical security of radiological material; protect vulnerable places from attack; increase resilience in the event of an attack and intercept dangerous materials before they reach their intended target. Priorities therefore include detecting the illicit trafficking of radiological material across borders, locating suspect devices and materials so that they can be disabled and made safe, and detecting ionising radiation as part of incident response. The UK Government is introducing radiation screening at UK borders and airports as part of Programme Cyclamen, a joint programme managed by the Home Office and

HM Revenue & Customs. The UK Government is also keen to further develop its nuclear forensics capabilities. CONTEST aims to mitigate the impact of an attack that cannot be prevented and the UK Government carries out multi-agency contingency planning and exercising, which includes an overseas observer programme.

1.6 Funding for nuclear security

DNDO's research and development programme includes fundamental research in nuclear science, as well as advanced technology demonstrations that apply laboratory research to practical field based problems. The DNDO's Academic Research initiative has provided 22 grants to 77 students. DNDO is also keen to reach out to other scientific communities beyond the field of nuclear science.

The Home Office has the responsibility for funding new research and development in the area of nuclear and radiological detection, although the Ministry of Defence has most of the technical capabilities and receives the majority of this funding. The UK Government has set up a CBRN Resilience Programme, which aims to provide personal protective equipment, mass decontamination capability and electronic personal dosimeters for all emergency and first responders in the event of a CBRN incident. £60 million has been made available to equip police and other first responders with protective equipment and in the New Dimensions Programme £56 million has been assigned to on mass decontamination capability at the scene. The 2007 Comprehensive Spending Review increased research and development funding in this area, including funding for the development of new detection technologies.

The European Commission has provided the IAEA with €200,000 to analyse criminal trafficking in European countries. This includes a study on the role of organised crime in radiological and nuclear trafficking in the EU and a study on detecting radiological and nuclear materials at novel points in their transfer other than border crossings. The EC has earmarked €200 million for the prevention and detection and response to illicit trafficking of nuclear and radiological material (Joint Research Centre, 2003). It has also provided funding for research and development at the EC's Joint Research Centre (JRC) institutes, including the JRC Institute for Transuranium Elements (ITU), which carries out research on nuclear forensics.

2 Key technical challenges

A brief overview of the major techniques for detecting nuclear and radiological material, to which these technical challenges apply, is provided in Appendix C.

2.1 Detecting shielded material

Radiation attenuation due to shielding is an exponential process and so even moderate amounts of shielding can have significant effects. At 10 metres, the radiation emissions of shielded gamma ray and neutron sources are at, or below, natural background rates in almost all cases.

The JASON group is an independent group of scientific experts that advises the US Government on the technical aspects of defence and security issues. A 2003 JASON study stressed that multiple techniques and methods are essential to detect shielded SNM, especially for shielded highly enriched uranium (HEU). This would include passive and active detection methods, as well as imaging techniques. Active methods could include active photon interrogation, using nuclear resonance fluorescence imaging, photofission and photoneutron methods. Radiography systems, such as the Vehicle and Cargo Inspection System (VACIS), supplemented by automatic cueing of X-ray image anomalies, especially materials with high atomic number, could also be used. The presence of shielding would then be a cue for further inspection, perhaps up to and including unpacking of cargo containers.

Muon detection is a very promising passive method for detecting densely shielded SNM, and muon imaging might also have an important role to play here.Cosmic ray muons have greater penetrative powers than gamma rays so are useful for detecting shielded SNM. 1 giga-electronvolt (GeV) muons can penetrate through thicknesses of up to 66, 44, 26 and 25 cm in iron, lead, uranium and plutonium, respectively. The key limiting factor is the time required for muon radiography, up to several hours to image only a cubic foot of a block of iron. According to a detector concept being developed by Los Alamos National Laboratory (LANL), it would take four minutes to image a cargo container. However, this would require detector panels perhaps the size of a large room. Moreover, once a shielded source has been identified it may take several hours to unpack the cargo to locate it.

2.2 Reducing false alarm rates

The current first generation approach for screening cargo for radiological material involves two levels of interrogation. Primary screening is undertaken with RPMs consisting of large polyvinyl toluene (PVT) plastic scintillators and moderated helium-3 (^{3}He) gas tubes to detect gamma rays and neutrons, respectively. They are gross counting devices to indicate quickly the presence of radiation above background levels but their gamma ray resolution is insufficient for isotope identification. This ensures a high throughput, operating at low vehicle speeds (5-10 mph). If radiation is detected, then the RPM sounds the alarm and secondary screening is then carried out. This is a slower process that provides more time for nuclide identification. Manual measurements are made using Radio-Isotope Identifiers (RIID) currently based on small volume sodium iodide (NaI) scintillator or cadmium zinc telluride (CdZnTe) semiconductor detector technology.

The major disadvantage of this process is the high false alarm rates (1-3%) of RPMs due to the high level of gamma ray emitting naturally occurring radioactive material (NORM). The Los Angeles/Long Beach port handles the importing of approximately 70,000 containers each week. This false alarm rate could give rise to up to 300 false alarms daily. This creates an additional operational burden and may reduce the confidence of the operator. Another drawback is the small size and poor geometry of RIIDs means that they may not be able to detect small sources. Since they are operated manually, their effectiveness also depends on how well they are positioned and for how long they are held over a given area. The whole process may take up to ten minutes since the RIID must be connected to a computer after measurement to upload the data for analysis.

One approach is to use advanced algorithms, such as energy windowing and spectral templates, to improve the energy resolution of NaI scintillators. For example, NucSafe Inc has developed software that rapidly compares the measured spectra against a library of known template spectra to find the best match. This library contains spectral templates for a prescribed set of nuclides, including NORM, industrial, medical and SNM prescribed by the application, and contain multiple templates for given nuclides to allow for the effects of shielding (International Atomic Energy Agency, 2006a). This method requires millisecond computer processing time but the spectral data gathered over 50 milliseconds could be far too sparse for reliable analysis. Instead it can be processed continuously every 50 milliseconds for a second or more, giving a time history of the identified nuclides. This enables a secondary inspection system to scan along the length of a moving vehicle to identify and even localise radiation sources.

Another approach is to use detectors with better energy resolution properties. CANBERRA Inc., for example, has developed prototype systems for DNDO's ASP Program to perform the dual roles of detecting and identifying radiological materials. The ASPs incorporate high resolution germanium scintillators and moderated ^{3}He tubes for gamma ray and neutron detection, respectively. They are electrically cooled and have integrated video imaging systems. Vehicles pass through the ASPs at 1-2 mph, taking up to 45 seconds; or if a slow scan is not operationally possible, then a tractor mounted with detectors can scan the vehicle, taking approximately 80 seconds. CANBERRA hopes that this will reduce the current false alarm rate of approximately 1-3% to 0.1% or less.

ORTEC Inc. has developed compact low-power hyper-pure germanium (HPGe) detector systems, which do not use liquid nitrogen cooling but miniature Stirling-cycle coolers. They have been designed for a long shelf life in the field and can operate for many hours using a rechargeable battery. They include self-contained digital signal processing and identification software for real time nuclide identification. Their size and weight depends on the size of the HPGe crystal. These systems can be used as part of a modular architecture. They are light enough for portable secondary inspection and mobile searches but can also be mounted for portal monitoring. However, these systems are expensive.

2.3 Measurement time

To ensure a free flow of commerce, the time available for measurement is restricted to about one second or less. This often produces sparse data for which special analytical methods are required. One solution is to aggregate detectors. For example, multiple large NaI detectors could be connected by Ethernet cables to process their output spectra together. The spectrum from each detector is collected in a short time period of around 50 or 100 milliseconds but if all the spectra are aggregated together, then the aggregate spectrum will enable a more precise analysis. When aggregating multiple detectors, their spectra need to be time synchronised and the energy scales of the spectra need to be identical. This could be achieved by including a signal of known and constant magnitude to calibrate the gain of the spectra in the detector.

2.4 Standoff distance

A free flow of commerce also requires radiation detection systems to meet measurement standoff distances typically of: a metre for pedestrians; several metres for vehicles and containers; and up to tens or even hundreds of metres for search applications. The intensity or flux of the source radiation decreases inversely with the square of the distance between the source and the detector. Therefore, real world applications often require large area detectors or detector arrays to compensate for the effects of standoff distances that range from one to hundred metres.

Pacific Northwest National Laboratory (PNNL) has been developing a long-range detector with a large surface area made out of parallel ^{3}He tubes. It has a collimator on the front and sides, and shielding material on the back. The collimator is a boron-10 (^{10}B) coated aluminium hexagonal (honeycomb) grid. Only neutrons that are travelling nearly parallel to the grid holes will pass through them, thereby reducing the effects of background NORM and enhancing directional sensitivity.

Neutron scatter cameras are currently under development to differentiate between low and high energy neutrons. This is to remove background neutrons so that neutrons can be detected from greater standoff distances. Neutrons scatter off protons in scintillators and, using kinematics, the energy of the incoming neutron and its direction can be determined.

3 Foreseeable technological developments

3.1 Near term: 3-5 years

Commercial vendors will require near term solutions to use existing or proven detection technologies that can be optimised to find radiological materials under real world conditions. For the large scale deployment of radiological detection systems, assessments must be made of value for money with respect to the cost relative to fitness for purpose. The larger size of systems used for detection at stand-off distances places constraints on the use of costly advanced detector technologies, whereas handheld and pager sized instruments may employ these due to their smaller size.

Low cost detectors with improved energy resolution will remain a key priority. These include new scintillators that use advanced deconvolution algorithms or are impregnated with new neutron sensitive dopants. Oak Ridge National Laboratory (ORNL) has been developing organic scintillators doped with neutron sensitive ^{10}B and gadolinium-157 (^{157}Gd) nuclides. Nova Scientific has been developing ^{10}B impregnated microchannel plate detectors as part of an electron multiplier structure. HPGe detector systems remain the gold standard for gamma ray spectroscopy. New developments in the cooling of HPGe systems show promise for improving their utility and broadening their field applications.

Major near term developments are likely to be in the use of passive and active coincidence detection methods to discriminate between neutrons and gamma rays, and the development of neutron imaging to localise sources. ORNL has also been developing zinc sulphide and lithium epoxy wavelength shifting fibres. These detect photons from the epoxy to provide positional information about incident neutrons. PNNL has been researching proton recoil in plastic scintillators to detect unmoderated fast neutrons. This uses pulse shape discrimination and time of flight differences to discriminate between neutrons and gamma rays.

Participants also noted the value of smart containers, in which gamma ray and neutron sensors are embedded to provide radiation measurements during transport. There would need to be indelible, machine-readable identification of cargo containers, as well as seals that are keyed to radio frequency identification tags to transmit information about any tampering and illegitimate opening of the container. Both technologies are technically and economically feasible.

3.2 Medium term: 5-10 years

In the medium term, there are promising opportunities to develop new technologies, such as muon detection systems. The All-Russian Research Institute of Automatics (VNIIA) is currently carrying out research on sophisticated geometry detectors, such as hodoscopes for detecting fast and thermal neutrons and gamma rays, and position-sensitive detectors for muon radiography. Participants felt that the potential of muonic X-ray and neutron detectors would be greatly assisted if portable accelerator sources of muons were available. It was noted that there is extensive muon expertise from work on the Large Hadron Collider at CERN (Conseil Européen pour la Recherche Nucléaire).

Cosmic-ray generated neutrons have already shown some promise for industrial applications where long measurement times are practicable. There may be a role for techniques, such as muon tomography, to provide in situ detection, thereby exploiting the much longer time available for screening during transit than at the port itself. The use of detectors in aircraft to monitor the levels of cosmic ray radiation could be applied for detecting onboard SNM.

VNIIA is carrying out research on radiography systems using portable neutron and X-ray generators. Other research at VNIIA includes: new charge-coupled device (CCD) detectors for cone beam radiography and tomography; detectors for simultaneous X-ray and fast neutron imaging; and a Localization and Identification of Neutron Emitters (LINE) detector. Lawrence Livermore National Laboratory (LLNL) is also developing a compact and possibly portable Compton camera but a field-deployable prototype remains a few years away.

3.3 Long term: 10-20 years

In the longer term, new base materials for scintillators could be developed, benefiting from advances in nanotechnology and semiconductors, such as quantum dots and organic semiconductors. VNIIA has been carrying out research on luminescent material, using composite scintillating fibres, strips, or sheets. Two new approaches also include the use of composite materials containing quantum dots with plasmon excitation, and use of composite materials containing rare earth phosphors and chalcogenide quantum dots. Sandia National Laboratories has developed direct electronic detection methods using organic semiconductors, in which electrodes are embedded in radiation sensitive polymers. This eliminates the need for optics and vacuum tubes and can enable high spatial resolution imaging.

Active interrogation methods could be developed, using mobile muon sources and exploiting backscatter photon (PIPAR) methods. Active sources could also be improved, such as tuneable narrow line-width X-ray sources (laser electron backscatter) and directional neutron sources. Participants noted the potential for exploiting active interrogation sources from other fields of application, such as the mono-energetic neutron sources used in oil well logging and high energy X-ray sources employed in industrial radiography.

4 Systems analysis

The physics of radiation sources, propagation, and detection is well understood and detector technology is relatively well developed. The JASON study concluded that dramatic improvements in detector technology are unlikely and that small improvements will only lead to marginal increases in overall systems effectiveness. Therefore, they observed that systems issues are more important for increasing overall likelihood of detection and therefore the efficacy of detection measures. These issues can be highlighted through systems analysis underpinned by powerful information technologies, two key components of which are networking and simulation of detectors.

4.1 Networking detectors

Detection systems and networks can be informed by other systems that use non-radiological modalities or are targeted at non-radiological material. The experience of screening for high explosives at airports illustrates that false alarm rates can be reduced significantly if detection systems are networked. Bayesian statistics demonstrates how the Receiver Operator Characteristic performance of networked systems can be significantly better than that of its individual members. If detection systems are networked, then the probability that a threat is detected across the whole network increases. Further details on this topic are provided in Appendix C.

A major challenge facing detection networks will be the fusing and exchanging of the data volumes produced by each system within the network. Improvements to detector technologies will need to include improved capabilities to interface with data handling and analysis capabilities.

Appropriate network protocols will also be required, which will need to take into account the limitations of each of the detector technologies. When networking detector technologies, quantitative data on the false alarm rates of the detection systems will need to be obtained from the manufacturers. Permitting communication of this information without compromising manufacturer's proprietary interests is an issue that will need to be addressed.

Detection networks for radiological and nuclear material could draw on pre-existing networks, such as radiation safety environmental monitoring. They could perhaps be integrated into other existing sensor networks. For example, a US company has a patent for putting radiological detection monitors on CCTV surveillance cameras and DNDO has begun a project networking mobile phones incorporating detectors. The capability of radiological detector systems to be integrated with other detection systems is important if ubiquitous radiological, nuclear and chemical and biological detection is to be achieved. The Home Office is considering integrating chemical, biological, radiological, and nuclear (CBRN) detection equipment into police vehicles. The integration of multiple sensors into one detection system permits the sharing of the power supply, computer and communications sub-systems. It also reduces the number of systems that must be bought, maintained and used by field personnel.

Effective networking does not only concern connecting detector hardware but is also dependent on networking amongst the people who design, deploy and operate the hardware and networking of the data that is generated. It is important to improve mechanisms for communication in all directions along the chain of command within and between organisations, including the academic, industrial and governmental sectors. Increasing interdisciplinary communication between the radiation physics community and other scientific fields, such as the biology and mathematics communities, would be beneficial. Valuable lessons could be learnt from detection networks used in these fields, such as environmental monitoring and disease surveillance. It is equally important that there is open communication between technologists and practical operational specialists.

Examples of effective networking already exist. These include IAEA information exchanges, bilateral agreements with neighbouring countries, international exercises, and international scientific community exchange programmes. Cultural and institutional differences with regard to the assessments and prioritisation of nuclear and radiological threats present major obstacles to developing detection networks. Forming networks could even increase threats by revealing sensitive information, including the network's own vulnerabilities. Institutional secrecy and the reluctance to share sensitive information in certain organisations and communities presents significant barriers to effective networking that need to be addressed.

Building trust between all stakeholders is a precondition for effective networking. A good first step would be to set up small, informal groups before building larger collaborations. Establishing a governance, risk, and compliance framework for radiological detection could also be useful to help integrate the various aspects of the detection architecture.

Networking requires common understanding and sharing of the concepts that define the context of the network and the content of the information. This could even include clear definitions of what can and cannot be shared, including prior agreement upon threat signatures and detection technologies as well as international risk assessment, scenario evaluation and systems modelling. It also entails sharing results to ensure that detector system performance at the laboratory level can be reproduced in field conditions. Information about alarms must be shared and standard operating procedures are necessary, especially in the context of emergency response. Standardised certification, testing, trialling protocols for detector systems are also important.

4.2 Simulations

Validated simulation tools using faithful models are essential to inform the design of detector system before hardware is constructed. For example, simulation of detectors is a well developed capability routinely practised in the course of basic nuclear and high energy physics research. No sophisticated detector in these fields is constructed until acceptable performance has been simulated. Any new radiological detection technology should be simulated before being fielded in order to anticipate and eliminate unsuitable and expensive prototype systems, including sources and detectors. The simulation process should incorporate a number of elements.

First, key parameters need to be defined. These include: the threat; performance metrics, such as the detection and false alarm probabilities, as well as the level of throughput; and the system, such as the nature and location of detectors, the different layers of the detection technologies, and secondary screening paths.

Second, simulations should be run using varied parameters to explore cost and performance tradeoffs. Factors that need to be considered here include, amongst others, economic costs, regulation, organisational culture. Comparisons should be made with other non-technical methods to counter the threat.

There are various steps that a malign actor would have to accomplish to smuggle and then deliver a nuclear device. These include: the decision to use SNM; acquisition of SNM (or a nuclear weapon); transportation within a country or across borders; and delivery to the target location. There are a number of tools of various efficacies within a layered system that could be used to prevent this worst-case scenario at various points in the timeline. In order of timeliness and decreasing leverage, these include control of SNM through physical protection and accountancy at storage locations; intelligence capabilities, including transport data; customs operations, including smart containers and more agents at home and abroad; deployment of detectors at various nodes; and inspection and unpacking of cargo.

The 2003 JASON study looked at methods to counter the potential smuggling of SNM into the USA and concluded that the greatest leverage at present is to scan, using existing and commercially available technologies, a much greater number of containers arriving at US ports. The report recommended that all containers entering the USA could be radiographed in dual mode (transmission and backscatter) at reasonable cost and delay. It stressed that implementation this strategy would not be a question of new technology but rather of creating the right incentives and regulations to motivate the commercial entities involved.

The JASON study emphasised that it is more important, in terms of resource allocation, to take a systems approach to evaluating the costs and benefits of any particular protection measure than to build many prototypes. To determine the optimal investment, the JASON group used a model of successive, independent screening stages, each of which has its own probability of detection and false alarm, the probability of failure of the entire system is the product of the individual failure probabilities. Given a fixed amount of resources, simple calculation shows that the failure of the entire system is minimised when all layers have an equal marginal improvement per unit cost spent. Therefore, investment should be concentrated on areas likely to yield the greatest marginal improvement of security for a given cost.

In a layered network of independent detection technologies, the optimal allocation of fixed resources is when they are spread evenly across the network. Costs need to be considered at each point within each layer and include research, development test and evaluation; capital; operational; and efficiency costs. This could lead to deploying different technologies of various degrees of sophistication at different nodes in the network.

Third, simulations of threat scenarios, so called red-teaming, need to be run to identify vulnerabilities in the overall detection system. This is an essential tool for verifying, monitoring, and improving overall system and network effectiveness, and should be carried out regularly. The results of these simulations need to be evaluated at a multi-agency level to militate against vulnerabilities by developing the most practical investment strategy that has the right mix of technical tools and practical approaches.

Fourth, based on these simulations, prototypes detectors should be constructed fielded and validated. Finally, the best prototype should be deployed.

In this way, systems analysis can guide the most effective deployment of different detector technologies. The screening of cargo containers at ports has different technical requirements, for example, than those of first responders arriving on the scene of an urban radiological emergency. This systems approach would allow for deployment of high-tech detection methods, such as active interrogation techniques, that are not routinely used because of cost and safety concerns, to be used in particular high-priority circumstances.

In Europe there are few international borders among Member States and so there is a need to focus on deployment equipment at key trafficking nodal points. An important issue is to connect detection at borders and ports to detection and tracking along national and international distribution networks. A mixture of high- and low-tech systems deployments may be useful. Sophisticated high-tech mobile detectors could be deployed in priority areas or when intelligence points towards a requirement for them rather than installing this (generally more expensive) equipment universally at every border and port all of the time. Secure wireless connectivity to command centres is increasingly desired to automate detection and remove the operator. This has valuable application for detection in remote locations.

Modular detection system architectures are valuable since portal configurations need to accommodate a range of scenarios, whether for screening single or dual traffic lane, cars or high sided truck traffic, or pedestrians. Vehicle based, airborne systems, boat mounted systems, as well as novel portable platfoms, such as suitcase and backpack systems, can play different roles at various nodes in a detection network. The latter have applications for radiological detection in crowded areas and at major public events.

5 Aerial detection

5.1 Existing systems

Aerial detection platforms include fixed wing aircraft, helicopters and unmanned aerial vehicles (UAV) and detection systems tend to use externally mounted high resolution scintillation detectors to exploit a larger field of view. This increases the area survey rate so that more readings can be taken of a larger area in a given time. As the distance between the detector and the source increases, radiation flux is attenuated in air and scattered radiation builds up. This eventually limits the effective working distance from which a given source can be detected.

High energy gamma radiation, above a few hundred keV, can be observed up to a distance of approximately 100m above ground. Lower energy radiation limits the potential for airborne observations to altitudes of 30m. SNM could be detected from the air in open spaces through the radioactive signatures of uranium-235 ($^{\mathbf{235}}$U) and the plutonium decay product, americium-241 (^{241}Am). These emit low energy gamma rays and require operational altitudes as low as 10-30 m.

For data to be recorded and collected, survey parameters need to be defined, including: sample time; ground clearance; speed; line spacing on a grid map; and area survey rate. Once collected, data must be processed in real time to include data validation, spectral analysis, and mapping, so that results can be obtained within the first few hours or sooner after landing. This is necessary due to the time constraints for effective reponse in the early stages of an incident or accident.

5.2 Emergency response

Airborne radiation surveys have a well developed history of use with applications ranging from mineral exploration and geological mapping, to fallout mapping, nuclear site characterisation and source searches under diverse conditions. They have a key role to play in emergency response to map areas after contamination, and UAV platforms are particularly suited to this application. The Israeli Caspar UAV prototype can fly at a height of up 700 m at speeds of 20-85 km/h for up to 1.5 hours, and its field of view is over 10 km. The Caspar includes an off-the-shelf, combined gamma and neutron CsI(Tl) (caesium iodide doped with thalium iodide) radiation detector, in addition to a camera and a global positioning system (GPS). It can fly at low altitude and transmit both its detection data and position in real time to a ground based team. Advantages of UAV systems are that they are light weight and can be deployed rapidly from any site. They are also considerably less costly to operate than aircraft and helicopter based systems. Being unpiloted and remote-controlled, they minimise radiation exposure to personnel and can even be disposed of afterwards if contaminated. These features make UAVs ideal for fast scanning and mapping of large contaminated areas, and monitoring and sampling radioactive plumes.

5.3 Urban surveys

Aerial detection has an important role to play in urban surveys and the manoeuvrability of rotary-wing systems means that they are particularly suited to this role. Helicopter based systems allow survey flights to be performed at low altitude of 50 m in open space and 100 m in urban areas, and at low speeds of approximately 70 km/h to ensure uniform coverage and to provide high detection sensitivities. A typical helicopter based system might incorporate at least one germanium detector, as well as NaI detectors, a radioaltimeter, and a GPS. These detectors need to be light, compact, and modular so that they can be easily attached to the helicopter.

Urban surveys present particular difficulties due to the high levels of background NORM in cities. In the built urban environment, there are many point source signals and so aerial detection can trace a source to a general area but not to a particular building. A two-tiered detection approach is a potential solution to this problem, using aerial detection to identify hotspots followed by vehicle based and other mobile systems to isolate the location of sources for further investigation.

5.4 Vehicle and mobile systems

The smaller fields of view of vehicle based and other mobile systems allow for a greater level of detail in detection operations to complement wide-range airborne systems. Vehicle based systems, as well as novel mobile platforms, such as suitcase and backpack systems, are more useful for variable terrain in cities and urban areas. However, deployment of these mobile systems is more labour intensive and time consuming.

5.5 Novel applications

Airborne detection systems are valuable in protective and responsive roles when used in combination with other approaches, especially as part of a layered detection network. They can be particularly suited to protecting focal points, such as high-value facilities or key buildings. Intelligence plays an essential part in assisting searches for materials and devices, including updates once items have gone missing. Safeguards programmes may also provide useful forewarning.

Tethered balloons and masts could provide elevated continuous detection over focal points. These may include important buildings, ports of entry and places where crowds gather for events. Airships could also provide a useful platform for urban surveys.

Participants felt that there was a minimal role for adapting instrumentation to detect ionising radiation emitted from SNM using space based platforms. The only area that might merit further consideration could be the detection of Cerenkov radiation or fluorescence generated in the vicinity of sources that are able to penetrate the atmosphere. Remote satellite imaging may however have a potential role in monitoring declared nuclear materials and facilities, and identifying supply networks.

5.6 Future research and development priorities

Baseline surveys of nuclear sites can show features related to fission products, activation products, fuel cycle products, machine sources, including shielded or collimated signals, under conditions which simulate urban areas. However, there is a need for greater attention to urban surveys where further operational studies and response modelling is needed.

A regular programme of baseline mapping is essential to provide the location of fixed radiation sources before an incident or emergency. For example ongoing background radiation surveys are taken of nuclear sites in France. Some participants felt that the results of aerial surveys could be published for method validation, as well as educating and encouraging greater public understanding of the radiological environment of normal life. Baseline mapping therefore has an important role to play in enhancing resilience.

The performance of aerial detection systems in source searches during international excerises has often been much lower than the theoretical performance capacities of sytems tested. Simulation and training exercises are key to using systems to their fullest. These can also provide important opportunities to enhance data exchange and to improve inter-operability under time constrained conditions. More systematic work is needed to improve response models and survey interpretation methods, particularly with regard to urban areas and radiation transport visualisation. Further modelling of operational scenarios may be helpful since search capacities that can cater for many scenarios are needed. Ideally such scenario modelling would be carried out at the international level.

6 Nuclear forensics

Nuclear forensics is a multidisciplinary field, drawing on analytical methods adapted from safeguards, materials science, and isotope geology to investigate nuclear or radiological material for its isotopic and elemental composition, geometry, impurities, macroscopic appearance and microstructure. This information can be used to establish the material's age, intended use, and method of production. Establishing the material's age, surface roughness and identifying the reactor in which it was used are key signatures needed to determine: when the material was last chemically processed; if it was formed as fuel in a nuclear power reactor; and what type of reactor it was burnt in. If all this information can be compared with external reference data, then it is possible to determine where the material was produced. From that information, it may be possible to deduce its last legal owner, and the smuggling route.

Nuclear forensics plays a central role in linking the prevention, detection, and response components of the nuclear security architecture, and ensuring its sustainability. This field has different research and development requirements to detection technologies that need to be supported. Reliable attribution leading to prosecution presents a strong preventative deterrent to potential smugglers. It also highlights vulnerabilities in the safeguards and physical security measures at the place of theft or diversion, which could then be strengthened to prevent future incidents. The Nuclear Smuggling International Technical Working Group (ITWG) is a multi-agency, interdisciplinary group, which advances the science of nuclear forensics as an integral part of the incident response process.

6.1 The Nuclear Smuggling International Technical Working Group

The ITWG was founded in 1996 and it reports informally to the G8 Nuclear Safety and Security Group. ITWG is overseen by an Executive Committee of six members representing the European Commission, France, Hungary, UK and USA. It also works closely with the IAEA. The ITWG provides an international forum for nuclear forensic experts to work together with law enforcement, first responder and nuclear regulatory professionals. The ITWG developed a Model Action Plan to systematise nuclear forensics work, and this has provided the basis for an IAEA technical guide (International Atomic Energy Agency, 2006b). This technical guide has been adopted by many member States in their response to incidents of illicit trafficking. It describes how the ITWG can provide States with nuclear forensics support with the IAEA acting as the broker.

6.2 Key technical challenges facing nuclear forensics

Identifying radioactive material at a given scene is difficult since the range of potential threat materials is vast. This can be significantly improved by pre-intelligence. Another complication is the quantity of the threat material, which could vary from tonnes to nanogrammes. Improving capabilities to detect tiny amounts of threat material would be valuable.

Maintaining the integrity of the physical material at a crime scene is important if it is to be used as evidence. This includes both the seized nuclear material and associated contaminated materials. In cases involving contaminated scrap metal, the metal can sometimes provide a more useful signature than the nuclear material. The ITWG has developed best practices for incident response, such as techniques to collect and preserve evidence, initial on-scene categorisation, identification of applicable laws and statutes, and assistance in nuclear forensic investigations.

Maintaining the chain of custody of material during transport is vital to ensure the integrity of evidence for potential prosecutions and to avoid cross contamination and health and safety hazards. A certain amount of analysis can be carried out at the scene to provide faster results before transfer to a controlled radiological laboratory. A response team could be equipped with basic hand-held radioisotope identifiers. Alternatively, a support vehicle could be deployed equipped with alpha and gamma spectrometry equipment. A more sophisticated on-scene vehicle based response capability could make use of equipment to prepare samples for higher resolution alpha and gamma spectroscopy.

Fusing data from various sources is essential for the success of nuclear forensics investigations and subsequent attribution. These data include: assessments of the crime scene or event; technical data gathered from technical analysis of the material; expert knowledge; intelligence and law enforcement information; and international nuclear forensics databases.

6.3 International nuclear forensics databases

Sharing of international material databases will help address the global threat of illicit trafficking of nuclear an radiological materials. These contain technical information about characteristic features of civilian and military nuclear materials and fuel cycles from around the world. Access to international databases would make attribution more accurate and robust, as well as significantly reducing the time taken for attribution. If a nuclear device was detonated, attributing the exact origin of the nuclear material used would likely take several months. Conceivably it could take a matter of days to weeks if shared databases are made available.

The ITWG aims to develop a secure meta-database. In the case of an incident investigators would contact this meta-database for reference information, thereby limiting the need for widespread sharing of sensitive information. There are considerable commercial and national security sensitivities over access to this data. A major challenge is how this data can be accessed in the most secure way. Advanced information technologies will have a crucial role to play here.

The ability to obtain good samples is crucial, especially if they can be quickly collected from radioactive plumes and fallout. Currently material databases contain a significant amount of information about the geometries of nuclear fuel pellets. However, more technical data is needed on powdered materials.

6.4 *Policy challenges and opportunities for nuclear forensics*

A renewed effort is being applied to nuclear forensics and post event attribution. If detection fails and the detonation of a nuclear device or weapon occurs, then nuclear forensics personnel will be under severe political pressure to determine the source and origin of the material and weapon. Nuclear forensics analyses of interdicted material, therefore, provide vital opportunities to practice and develop capabilities to provide rapid findings.

In the event of a nuclear detonation, there would be an inevitable conflict between the constraints of the legal framework for forensic investigation on the one hand, and the political desire for a quick resolution as well as the need to protect public health. Decision criteria to resolve this conflict will need to be available and should have been discussed and agreed upon in advance rather than during a crisis. This emphasises the need to address the relevant technical challenges to enable significant policy decisions to be made ahead of time.

Nuclear forensics has a role to play both in counter-terrorism activities and in non-proliferation and arms control efforts. It has a potential role in verification of the Comprehensive Test Ban Treaty and other elements of nuclear weapons arms control and disarmament efforts.

7 Key cross-cutting issues

7.1 *Increased international cooperation and coordination*

Global nuclear security threats require global capacities to address them. International cooperation and coordination are essential in coordinating responses and in sharing scientific expertise and detection technologies where necessary. The IAEA aims to assist Member States with their nuclear security efforts by providing technical support upon request. The IAEA is preparing guidelines for improved detection measures and is also promoting relevant research and development within Member States. Appropriate equipment needs to be acquired in parallel with a sustainability plan for that equipment.

Proper international arrangements for training and maintaining qualified people in all relevant organisations must be put into place. This is particularly important as some States do not have the resources, technology, and expertise to address nuclear security threats effectively. The 2006 polonium poisoning incident in the UK also illustrated the potential for a more widespread attack to overwhelm the response system even of a country with advanced technologies and expertise.

7.2 *Shared threat assessments*

Cultural and institutional differences in characterising and prioritising threats are major obstacles to establishing a global nuclear security architecture. Shared threat assessments, which must be based on intelligence and scenarios, can go some way to overcoming these problems. Threat assessments at the national level should be complemented by joint assessment exercises at the regional and international levels. A priority at the European level is the need to reassess the adequacy of existing detectors that were installed in the early 1990s but may not be suitable for contemporary threats. The EC's Directorate General for Justice, Freedom and Security supports and co-ordinates efforts by member States to detect nuclear and radiological material. In 2008, the EC will establish a CBRN task force with representatives from various sectors, including academia and industry, to develop an action plan to address nuclear security and detection.

These assessments should direct the development and deployment of detection technologies by prioritising: what type of material needs to be detected; how much material needs to be detected; what types of detectors are required; and where detectors could be most effectively deployed. The most appropriate technologies will depend on the nature of the material to be detected and the given situation, and so they need to be deployed in a targeted manner according to the specific threat scenario. Detection needs are currently not well defined and so shared threat assessments would help to identify and prioritise capability gaps. These would also provide industry and the scientific community with well-defined technical requirements to guide research and development, which would help avoid unnecessary duplication of costly funding efforts.

7.3 Coordinated certification and testing

Greater exchange between States in the areas of certification, testing and trialling of detection systems will help to build confidence so that States can trust the quality of each other's measurements and avoid unnecessary duplication of scanning. Central to this is the need for internationally agreed functional specifications for detection equipment, underpinned by agreement on threat assessments. Universally available, robust, and independent testing and evaluation processes are needed to avoid reliance on testing carried out by the equipment manufacturers or vendors. This testing should be carried out not only under controlled laboratory conditions but also under field conditions. The European Commission Joint Research Centre (JRC) in Ispra, Italy, conducted some testing on detection equipment and found gaps between claimed and actual performances. During 2008 the EU is making €1.6 million available in grants for certification, testing, and trialling of detection systems.

The IAEA tests all detection equipment procured through it by member States. The IAEA's Illicit Trafficking Radiological Assessment Program (ITRAP) provides independent certification of radiation monitors. One problem that has been raised is the high cost for small companies to certify their detection systems. The EC has recognised this issue with ITRAP and is developing a 'one stop shop' for testing and information exchange about equipment performance. This would provide a lower cost solution than each EU member State testing its own equipment and would set a common standard across member States. US companies are also required to pay to participate in assessment exercises to test their equipment for various US Government agencies, which places a significant financial burden on small businesses. A system of certified US laboratories is being established that can be used by companies to test their equipment, although they will still need to pay for the use of these facilities.

There is also a clear need for countries to identify and exchange best practices in: training methodologies, processes and procedures for responding to the detection of radiological sources, including training for first responders; and processes related to the operation of detection systems including relevant training. The latter is important to ensure that the utility of a given detection system is maximized by correct operation and handling.

7.4 Fostering networking

Developing increased trust between States is fundamental for all cooperative and collaborative efforts on radiological and nuclear detection. Academic and technical exchanges should be encouraged to aid development of wider cooperation in this area. Participants agreed that meetings, such as this workshop, are helpful in bringing together a diverse group of policymakers, scientists, and industrialists.

Some participants felt that international collaborative support can be difficult. The US model for collaboration among universities, national labs, and industry was highlighted, such as the Small Business Innovative Research (SBIR). Increasing interdisciplinary communication between the radiation physics community and other scientific disciplines would also be beneficial, especially to promote novel approaches to detection.

It is equally important that there is open communication between policymakers and scientists, so that the former can define the requirements for detection systems. It was suggested that in the UK the Home Office, Ministry of Defence and Research Councils could try to bring academics, policy makers and companies together to look at the problem of radiological and nuclear detection.

Participants recognised the lack of knowledge among scientists and technicians about the real world problems that need to be solved. The requirements and priorities with regard to detector systems will vary according to manufacturer, policymaker, and end-user, and may well conflict. The priority for policymakers may be that no material is smuggled at all but for front line end-users it may be to decrease false alarm rates.

7.5 End-user training and feedback

Front line operators, such as customs officers, and first responders need to be trained in the physical characteristics of radioactive and nuclear sources to increase their understanding about how to recognise them. Training may also be needed to address the operation of detection equipment and procedures to be enacted in response to an alarm. There are also cultural problems in terms of changing the ways that front line operators work. Customs tend to intercept only a fraction of contraband sufficient to deter potential smugglers, as demonstrated by the continued success of smuggling activities. For nuclear devices, the interception requirements are much more stringent. However, it is important to make the best use of the innate investigative skills of front line officers and first responders.

The practical needs of non-expert front line operators must be communicated to scientists and policymakers. Equipment needs to work in often difficult operational circumstances and needs to be sufficiently robust and reliable for harsh environmental conditions.

The level of training for front line operators, as well as the cost of equipment maintenance needs to be taken into account when considering the merits of deploying more advanced technologies. For example, the analysis of spectral data to identify a given source can be automated when using advanced equipment. However, it is still advisable to have a trained analyst review the data in the case of a secondary or tertiary alarm. One potential solution would be for the data to be transmitted remotely to an expert off-site.

7.6 Raising awareness and educating about nuclear security

Sensible public education about nuclear and radiological threats is vital to build trust in government threat assessments. It would also build resilience and avoid a disproportionate public response where the threat to public health may be relatively low. The vast differences in consequences between nuclear and radiological incidents need to be clearly communicated. National vulnerabilities should not be exposed inadvertently but even if specific information is too sensitive for public discussion, details about general threat assessment processes and methodologies should be openly discussed.

7.7 Engaging the scientific community and maintaining a skills base

There are concerns that there may not be sufficient skills and expertise available to sustain radiological detection research and development activities, and so more people need to be trained in the area of nuclear security. Some participants felt that a possible global revival in nuclear power would help create new job opportunities and university places, and that there was a growing recognition of the importance of nuclear security, which would renew interest in this area.

It was noted that the IAEA engages with the scientific community through Coordinated Research Projects. This programme of research includes the development and implementation of radiological detection instruments and methods, as well as the improvement of technical measures to respond to incidents, especially through the application of nuclear forensics.

7.8 Funding

Participants felt that governments must fund research and development for novel detection systems but highlighted the lack of a clear coordinated activity for fundamental funding in the area of radiological and nuclear detection. Participants agreed that there was need to engage the high-end research community in order to ensure funding for research programmes.

Some participants felt that funding for equipment development does not always take into account the needs of first responders. It was noted that although military technologies tend to be more advanced than technologies for civilian use, the former do not very often translate well into the latter.

8 Key points and conclusions

- The detection of nuclear and radiological materials is one facet of a multilayered defence against nuclear security threats, which also requires robust prevention and response elements. Information sharing, especially of good intelligence, is central to all aspects.

- In the near term (3-5 years) low cost detectors with improved energy resolution for gamma ray spectroscopy will remain the key priority. Germanium based detector technologies remain the gold standard and developments in cooling will improve and broaden their field applications. In the medium term (5-10 years), there are promising opportunities to develop new technologies, such as muon detection systems. In the long term (10-20 years) detection could benefit from advances in nanotechnology and organic semiconductors.

- Systems analysis underpinned by powerful information technologies should inform detector design and increase overall system effectiveness. Simulations are essential for optimising the performance and deployment of different detectors. They can identify vulnerabilities and thereby help focus the allocation of resources. Networking detector technologies is an important part of this approach.

- Aerial detection systems are valuable in preventative and responsive roles. Unmanned aerial vehicle based systems show particular promise for emergency response and highly manoeuvrable rotary-wing systems are valuable in urban environments.

- Nuclear forensics capabilities need to be improved as reliable attribution leading to prosecution presents a strong preventative deterrent to potential traffickers. For robust and rapid attribution of radiological and nuclear materials the fusion of different technical and intelligence data is important, including sharing of international material databases.

- International cooperation is essential to develop shared threat assessments to help identify and prioritise capability gaps. Greater coordination is needed at all levels for research and development, certification, testing, and trialling of detection systems, as well as technology sharing and training. This will help reduce funding costs, avoid duplication of efforts, and build confidence in global nuclear security.

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Professor Roger Cashmore FRS (University of Oxford, UK)
Professor William Gelletly (University of Surrey, UK)
Professor Raymond Jeanloz (University of California Berkeley, USA)
Professor Francis Livens (University of Manchester, UK)
Dr Rob Sareen (e2v Instruments, UK).

We would also like to thank the other workshop Chairs, Professor John Ahearne (Sigma Xi, US), Sir Peter Knight FRS (Imperial College, UK), and Dr Paul Sellin (University of Surrey, UK), as well as all the speakers. Our thanks also go to Dr Micah Lowenthal and Mr Ben Rusek from the US National Academies for their reporting assistance during the workshop.

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Appendix A: Workshop programme

Day 1: Monday 10 December

Welcome and opening remarks
Mr Stephen Cox, Executive Secretary, the Royal Society

1 Radiological detection: the policy context
Chair: Professor John Ahearne, Emeritus Executive Director, Sigma Xi, USA

- **Detection of malicious acts involving nuclear and other radioactive material**
  Dr Anita Nilsson, Director, Office of Nuclear Security, Department of Nuclear Safety and Security, International Atomic Energy Agency, Austria
- **Radiological and nuclear threats: the UK's counter-terrorism strategy**
  Mr Steven Smith, Director, Office for Security and Counter Terrorism, Home Office, UK

2 Radiological detection at borders and ports: current capabilities and challenges
Chair: Professor John Ahearne, Emeritus Director, Sigma Xi, USA

- **Screening for radiation at US borders and ports**
  Dr Huban Gowadia, Assistant Director, Domestic Nuclear Detection Office, Department of Homeland Security, USA
- **Detection and radiological risk reduction**
  Dr Lukas Holub, Policy Officer, Fight Against Terrorism and Access to Information Unit, Directorate General Justice, Freedom and Security, European Commission, Belgium

3 Near-term radiological detection solutions
Chair: Dr Paul Sellin, Reader, Department of Physics, University of Surrey, UK

- **Near term solutions for neutron and low to medium gamma ray detection**
  Dr Rick Seymour, Chief Executive, Nucsafe, USA
  Dr Will Clark, Director, Oxford Scientific Software Ltd, UK
- **Near term gamma ray detection**
  Mrs Pat Sangsingkeow, Manger (charged particles detectors group) Advanced Measurement Technology, ORTEC, USA

4 Detecting hidden radiological material
Chair: Dr Paul Sellin, Reader, Department of Physics, University of Surrey, UK

- **2003 JASON study on detecting hidden nuclear material**
  Dr Roy Schwitters, Department of Physics, University of Texas at Austin, USA

5 Aerial detection

Chair: Professor William Gelletly, Department of Physics, University of Surrey, UK

- **The capabilities of airborne and vehicular gamma rays surveys to detect the illicit movement of radiological sources**
  Dr David Sanderson, Head, Environmental Physics Group, Scottish Universities Environmental Research Centre, UK
- **The capabilities of helicopter based gamma systems to detect radiological materials**
  Dr Ludovic Guillot, Head of Laboratory, Military Applications Division, Atomic Energy Commission, France
- **Radiation detection unmanned aerial vehicles**
  Dr Ilan Yaar, Vice Director, R&D Division, Nuclear Research Centre Negev, Israel

6 Novel ways to detect radiological material

Chair: Professor William Gelletly, Department of Physics, University of Surrey, UK

- **Requirements for detector systems for radiological and nuclear material detection**
  Professor Dick Lacey, Chief Scientist (CBRNE threats), Home Office Scientific Development Branch, UK
- **Detection of high atomic number elements using cosmic-ray muons**
  Dr Walter Gilboy, Visiting Senior Research Fellow, Department of Physics, University of Surrey, UK
- **Novel radiological detection networks**
  Dr Geoffrey Harding, Scientific Adviser, General Electric Security, Germany

7 Breakout session 1: innovative approaches to radiological detection

Each breakout group will focus on one topic each.

1. **Aerial detection, City of London Room 1**
   Chair: Sir Peter Knight FRS, Principal, Faculty of Natural Sciences, Imperial College London, UK
   Rapporteur: Dr David Sanderson, Head, Environmental Physics Group, Scottish Universities Environmental Research Centre, UK
2. **Novel detection methods, City of London Room 2**
   Chair: Professor Roger Cashmore FRS, Principal, Brasenose College, Oxford University, UK
   Rapporteur: Dr Walter Gilboy, Visiting Senior Research Fellow, Department of Physics, University of Surrey, UK
3. **Novel detection systems and networks, City of London Room 3**
   Chair: Professor William Gelletly, Department of Physics, University of Surrey, UK
   Rapporteur: Dr Geoffrey Harding, Scientific Adviser, General Electric Security, Germany

Day 2: Tuesday 11 December

8 Nuclear forensics

Chair: Professor Francis Livens, Director, Centre for Radiochemistry Research, School of Chemistry, University of Manchester, UK

- **Technical challenges facing nuclear forensics**
  Mr Peter Sankey, Head, Threat Reduction, Atomic Weapons Establishment, UK
- **International Technical Working Group to Counter Illicit Nuclear Trafficking**
  Dr Klaus Mayer, EC Joint Research Centre at the Institute of Transuranium Elements, Germany

9 Feedback from Breakout session 1: innovative approaches to radiological detection

Chair: Professor Francis Livens, University of Manchester, UK

Each rapporteur will give a PowerPoint report of their group's discussions.

10 International perspectives on innovation in radiological detection research

Chair: Dr Rob Sareen, e2v Scientific Instruments, UK

- **A comparison of technologies and recommendations for CANBERRA's advanced spectroscopic portals program**
  Mr Steve Mettler, Program Director (Advanced Spectroscopic Portals) and Business Segment Manager (Ports and Borders), CANBERRA, USA
- **International cooperation in the research and development of radiological detection systems**
  Dr Vitaly Mikerov, Head, Research Laboratory, All Russian Research Institute of Automatics, Russia

11 Breakout session 2: assessing innovative approaches and identifying future R&D needs

All three breakout groups will:
(1) Assess whether the innovative solutions raised can meet policy & technical challenges.
(2) Identify R&D priorities for the favoured solutions.

Breakout group Chairs, Rapporteurs and locations as for the previous breakout session 1

Coffee break

12 Feedback from the Breakout session 2

Chair: Professor Raymond Jeanloz, Department of Astronomy, University of California at Berkeley, USA

This final discussion session should also give some time for attendees to make final observations / reflections.

13 Closing remarks

Professor Roger Cashmore FRS, Principal, Brasenose College, Oxford University, UK

Appendix B: List of participants

Name	**Organisation**
Dr Uri Admon	Atomic Energy Commission, Israel
Dr Pete Adsley	Senior Scientist, Atomic Weapons Establishment, UK
Dr John Ahearne	Emeritus Executive Director, Sigma Xi, USA
Mr Peter Ainscough	Deputy Director, Nuclear Threat Reduction, Directorate General Strategic Technologies, Ministry of Defence, UK
Sir Roy Anderson FRS	Chief Scientific Adviser, Ministry of Defence, UK
Dr Rolf Arlt	Radiation Detection Specialist, International Atomic Energy Agency, ret., Austria
Dr Doug Beason	Associate Laboratory Director for Threat Reduction, Los Alamos National Laboratory, USA
Dr Sandra Bell	Director, Homeland Security and Resilience, Royal United Services Institute, UK
Dr Sergey Bogatov	Lead Researcher, Nuclear Safety Institute, Russian Academy of Sciences, Russia
Professor Roger Cashmore FRS	Principal, Brasenose College, Oxford University, UK
Dr Will Clark	Director, Oxford Scientific Software Ltd, UK
Dr Neil Davison	Science Policy Manger, the Royal Society, UK
Dr Dan Dietrich	The Radiation Technology Group, Lawrence Livermore National Laboratory, USA
Professor Ray Dixon FRS	Project Leader, Department of Molecular Microbiology, John Innes Centre, UK
Professor Clive Dyer	Chief Scientist Centre for Radiation Environments, Effects and Hardening, Space Division, QinetiQ, UK
Professor Laurence Eaves FRS	School of Physics and Astronomy, University of Nottingham, UK
Dr Nikita Egorov	Radionuclide Laboratory Leader, Moscow Engineering Physics Institute, Russia
Dr Caroline Evans Thompson	Senior Scientist, Atomic Weapons Establishment, UK
Professor Rod Flower FRS	Deputy Chief Executive, William Harvey Research Institute, Queen Mary, University of London, UK
Professor William Gelletly	Department of Physics, University of Surrey, UK
Dr Walter Gilboy	Visiting Senior Research Fellow, Department of Physics, Surrey University, UK
Dr Huban Gowadia	Assistant Director, Domestic Nuclear Detection Office, Department of Homeland Security, USA
Dr Ludovic Guillot	Head of Laboratory, Military Applications Division, Atomic Energy Commission, France

Dr Geoffrey Harding	Scientific Advisor, GE Security, Germany
Dr Alan Heyes	Director, Global Threat Reduction, Department for Business, Enterprise and Regulatory Reform, UK
Mr Lukas Holub	Policy Officer, Fight Against Terrorism and Access to Information Unit, Directorate General (Justice, Freedom and Security), EC, Belgium
Dr Sue Ion	Former Group Director of Technology, British Nuclear Fuels Ltd, UK
Professor Raymond Jeanloz	Department of Astronomy, University of California at Berkeley, USA
Captain Bryn Jones	Director, Solarmetrics Ltd, UK
Dr Johannes Knapp	Lecturer, Department of Physics and Astronomy, University of Leeds, UK
Sir Peter Knight FRS	Principal, Faculty of Natural Sciences, Imperial College London, UK
Dr Glenn Knoll	Professor Emeritus of Nuclear Engineering & Radiological Sciences, University of Michigan, USA
Dr Steve Koonin	Chief Scientist, British Petroleum, UK
Mr Ben Koppelman	Science Policy Officer, the Royal Society, UK
Dr Andrey Kuznetsov	Director, Nuclear Physics Department, Khlopin Radium Institute, Russia
Professor Dick Lacey	Chief Scientist (CBRNE threats), Home Office Scientific Development Branch, UK
Dr Francis Livens	Director, Centre for Radiochemistry Research, School of Chemistry, University of Manchester, UK
Dr Micah Lowenthal	Senior program officer, Nuclear and Radiation Studies Board, National Academies of Science, USA
Mr Stephen Mettler	Program Director (Advanced Spectroscopic Portals) and Business Segment Manager (Ports and Borders), CANBERRA, USA
Dr Klaus Mayer	Nuclear Chemistry Unit, Institute of Transuranium Elements, Germany
Dr Vitaly Mikerov	Head, Research Laboratory, All Russian Research Institute of Automatics, Russia
Dr Keith Mize	Senior Advisor for Nuclear Counterterrorism, National Nuclear Security Administration, Department of Energy, USA
Dr Anita Nilsson	Director, Office of Nuclear Security, Department of Nuclear Safety and Security, International Atomic Energy Agency, Austria
Professor Paul Nolan	Head, Department of Physics, Liverpool University, UK
Mr Steve Papworth	Strategic Technologies, Nuclear Threat Reduction, Ministry of Defence, UK
Sir Michael Pepper FRS	Chief Scientific Director, TeraView Ltd, UK
Dr Anthony Peurrung	Director, Physical and Chemical Sciences Division, National Security Directorate, Pacific Northwest National Laboratory, USA
Mr Robin Pitman	Head, Nuclear and Strategic Defence, Ministry of Defence, UK
Dr Joel Pouthas	Head, Instrumentation Division, Institute for Nuclear Physics, National Scientific Research Centre, France
Dr David Ramsden	Director, Symetrica, UK

Dr John Roberson	Nuclear Science Advisor, Directorate General Strategic Technologies, Ministry of Defence, UK
Mr Ben Rusek	Associate Program Officer, Committee on International Security and Arms Control, National Academies of Science, USA
Professor Brit Salbu	Isotope Laboratory, Dept. Plant and Environmental Sciences, Norwegian University of Life Sciences, Norway
Dr David Sanderson	Head, Environmental Physics Group, Scottish Universities Environmental Research Centre, UK
Mrs Pat Sangsingkeow	Manager, Advanced Measurement Technology ORTEC, USA
Dr Peter Sankey	Head, Threat Reduction, Atomic Weapons Establishment, UK
Dr Rob Sareen	Business Development Manager, e2v Scientific Instruments, UK
Dr Roy Schwitters	Department of Physics, University of Texas at Austin, USA
Dr Paul Selllin	Reader, Department of Physics, University of Surrey, UK
Dr Rick Seymour	Chief Executive Officer, Nucsafe, USA
Mr George Sherriff	Nuclear Issues Desk Officer, Counter Proliferation Department, Foreign and Commonwealth Office, UK
Dr Francoise Simonet	Project Leader, CBRN Counterterrorism Research, Atomic Energy Commission, France
Professor Geoffrey Smith FRS	Department of Virology, Faculty of Medicine, Imperial College London, UK
Mr Steven Smith	Director, Office for Security and Counter Terrorism, Home Office, UK
Dr David Thomas	Head, Neutron Section, National Physical Laboratory, UK
Mr Paul Thompson	Senior scientist (radiochemistry), Atomic Weapons Establishment, UK
Dr Malcolm Wakerley	Radioactive Waste and Emergencies Technical Advisor, Radioactive Substances Division, Dept for Environment, Food and Rural Affairs, UK
Dr Christopher Watson	Former Business Development Manager for AEA Technology in Russia, UK
Dr Victoria Wright	Science Strategy Team, Science and Technology Facilities Council, UK
Dr Ilan Yaar	Vice Director for Research and Development, Nuclear Research Centre Negev, Israel

Appendix C: Techniques used to detect nuclear and radiological materials

1 Detecting special nuclear materials

Highly enriched uranium (HEU) and weapons grade plutonium are commonly referred to as special nuclear materials (SNM). Field based methods to detect SNM exploit the properties of neutrons, and high energy gamma rays and X-rays. Alpha and beta radiation (helium nuclei and electrons, respectively) simply do not have the range to reach the detector and are too easily shielded. Neutrons are subatomic particles that are emitted from fissile nuclei, such as plutonium or uranium. Gamma rays and X-rays are both forms of high-energy electromagnetic radiation. One way to distinguish between them is by origin. Whereas gamma rays are emitted during the decay of radioactive nuclei, X-rays are emitted during the rearrangement of atomic electrons following the irradiation of materials.

Gamma rays and X-rays are potentially very useful since they combine good detection specificity with high detection efficiency. Gamma rays are of particular interest since they are emitted with high photon energies that provide a fingerprint or signature for each radionuclide. However, identifying the gamma ray signature of SNM is problematic since it can be heavily masked by the significant levels of gamma rays in the background of naturally occurring radioactive material (NORM). For this reason, spectrally resolving detectors with the highest energy resolution can be particularly useful in identifying SNM against a strong background signal. By contrast, the natural neutron background is significantly lower and more constant, making neutron detection a potentially more sensitive technique.

The spontaneous fission rates of the even mass numbered isotopes of plutonium and uranium are much greater than for the odd mass numbered isotopes. Plutonium-240 (^{240}Pu) and uranium-238 (^{238}U) fission spontaneously and so can be detected using passive methods, which do not require interrogation of the sample by irradiation but simply measure the intrinsic radiation emitted by the SNM source. Uranium-235 (^{235}U) and plutonium-239 (^{239}Pu), which constitute the bulk of HEU and weapons grade plutonium respectively, are better detected by active methods; for example, by using an external source of neutrons, photons, or charged particles to induce these isotopes to fission.

Active neutron interrogation methods use neutrons from industrial neutron sources, such as californium-252 (^{252}Cf), or a neutron generator. SNM nuclei generally emit high energy, fast neutrons (>5 mega-electronvolts (MeV)). By surrounding the source with neutron-moderating material, such as polyethylene, fast neutrons are slowed to become thermal neutrons (0.025 eV). These are more likely to be captured by SNM, increasing the likelihood of fission. Compared to radioisotope sources, neutron generators, such as DT (deuterium-tritium) tubes or linear accelerators, have the advantage that they are emission-free when powered down. Some of these generators may be small enough to be portable or transportable.

An alternative method of active detection is photofission, which uses high energy gamma rays (6-12 MeV) from an accelerator to interrogate the sample and induce fission. Upon irradiation, so called photoneutrons can be emitted immediately from nuclei by a nuclear fission event. Alternatively, neutrons can be emitted by the fission products from a few milliseconds to a few minutes later. Gamma rays of 10MeV can induce emission of these delayed neutrons, the detection of which is an unambiguous indicator of the presence of SNM. Nuclei can also fluoresce just like atoms and molecules. Thus another possible method for SNM detection is Nuclear Resonance Fluorescence (NRF), which can occur when excited nuclei decay by emitting electromagnetic radiation in all directions, the energy distribution of which is unique to the specific nuclear isotope. Detecting these photons and measuring their energy provides a unique identification of the sample.

Passive measurement systems are ideal for use in public areas but are typically more limited in sensitivity in comparison to active interrogation systems, which may not be suitable for measurements in public areas. Their production of radiation requires shielding, and the dose per analysis must be considered if people, such as front line officers, are routinely present or being scanned. The exposure of the samples will also be affected by regulatory controls on the level to which the items being inspected, such as food, can be irradiated.

Plutonium based weapons are generally more easily detected than uranium based weapons. Weapons grade plutonium is a relatively strong neutron emitter, most of which originates from the spontaneous fission of the small amount of ^{240}Pu present in the material. These neutrons can be shielded by large amounts of neutron moderating materials. The ^{235}U in HEU emits very few neutrons and its primary detectables are low-energy gamma rays but these are easily shielded. Finding methods of detecting shielded SNM, especially shielded HEU, is a high priority.

Neutrons and gamma rays are both long-range neutral entities and cannot be detected directly. However, gamma rays can transfer their energy to atomic electrons via the photoelectric, Compton scattering, and pair production processes. Neutrons can transfer their energy to short range charged particles such as protons and alpha particles. These secondary particles then produce measurable electrical signals in the materials of a detector that can then be displayed in an observable form. As radiation passes through a gas based detector, for example, gas molecules will be ionised, resulting in electrically charged species and free electrons. These migrate in an electric field to induce a current, which is measured directly and displayed as a signal. As radiation passes through scintillator detectors, valence electrons in the scintillator are excited to higher energy states, emitting photons of visible wavelength as they return to their normal energy states. These pulses of light, or scintillations, propagate through the detector until they reach a light sensitive device, such as a photodiode or photomultiplier tube (PMT). When photons of light strike the photocathode end of the PMT, electrons are produced, and each of these in turn promotes a cascade of many further r electrons as they pass through the PMT. This amplifies the strength of the electron pulse, which is then processed and converted into a signal that can be displayed as a spectrum.

2 Neutron detection

Helium-3 (^{3}He) gas tube proportional detectors are the industry standard thermal neutron detector. They consist of a sealed tube containing pressurised ^{3}He gas and are available in a variety of lengths and diameters and pressures. They require moderate operating voltage and have a significant power consumption. Their major disadvantages include their rigid geometry, slow response and sensitivity to vibration. They also need to be shipped as hazardous cargo.

Solid-state thermal neutron detectors, such as lithium-6 (^{6}Li) doped scintillating glass fibres, are now commercially available. The solid-state nature of the glass fibre means that they are not hazardous cargo. They are less sensitive to vibration and can be used for mobile and aerial applications or even as in-situ detectors built into containers and other cargo transporters. The key advantages over gas tubes are their flexible geometry and sensitivity. Glass fibres can be laid down in ribbons varying in length and number. Larger widths are made using multiple ribbons. They can contain up to tens of thousands of fibres, depending on the neutron intensity or flux to be detected. Each one is constructed of multiple layers of fibre interleaved with polyethylene. They are even sufficiently flexible to fabricate wearable devices.

The higher atom density of solid-state detectors means that they contain many more atoms than gas based detectors, making them more sensitive to neutrons. However, this also increases their sensitivity to gamma rays, which could lead to false alarms. When SNM fissions, neutrons are emitted in bursts with a mean number of about 2.5 neutrons per fission. Passive or active coincidence detection of the simultaneously emitted neutrons is therefore a useful method to overcome this problem, allowing weapons grade plutonium and HEU to be detected. Detection of coincident neutrons can be used to discriminate neutron events from other radiation.

3 Gamma ray detection

The main gamma ray detectors commercially available include organic polyvinyl toluene (PVT) plastic scintillators; inorganic sodium iodide (NaI) and caesium iodide (CsI) scintillators; and hyper pure germanium (HPGe) detectors.

Large area detectors provide high sensitivity. Good quality PVT scintillators of more than 1m in length can be manufactured inexpensively and easily, and they may be the only practical choice if continuous and large scintillator arrays are required, especially for primary portal screening applications. However, PVT scintillators have very poor gamma ray energy resolution, which makes them prone to high false alarm rates. NaI scintillators provide better gamma ray energy resolution. NaI is opaque to its own scintillation radiation. This restricts the size of pure crystals that can be used. To overcome this limitation NaI crystals are doped with thallium iodide (TI) to provide intermediate energy states into which excited electrons can be captured. The radiation emitted when these states de-excite is at a different wavelength, at which NaI is transparent. This allows the manufacture of NaI(TI) crystals in a variety of sizes but they are more expensive than PVT scintillators.

Semiconductor detectors using very large single HPGe crystals provide the best energy resolution by far and remain the gold standard for gamma ray spectroscopy. The major drawback is that they operate at cryogenic temperatures. Requiring liquid nitrogen cooling makes them heavy and difficult to use, restricting their applications to secondary or tertiary screening. A steady supply of liquid nitrogen poses logistical problems for remote deployments. Recent developments in mechanical cooling systems have alleviated some of the requirements for liquid nitrogen supply for HPGe detectors. However, deploying large arrays of HpGE detectors remains an extremely expensive option.

The development of new semiconductor gamma ray detectors that do not require cooling continues to be pursued commercially, principally, but not exclusively, using the compound semiconductor cadmium zinc telluride (CdZnTe). Initially developed as a spectroscopic gamma ray detector for medical imaging applications, it is anticipated that CdZnTe detectors will make a growing contribution to security imaging as the technology become more commercially mature. Although currently providing energy resolutions slightly worse than HPGe, the ability to operate these devices at room temperature and in tightly-packed geometries provides many potential advantages. CdZnTe detectors have an energy resolution approximately seven times better than NaI. However, it is currently only available in sizes nearly 1,000 times smaller than NaI crystals. Lanthanum (La) halide scintillators (LaCl3:Ce and LaBr3:Ce) have energy resolution approximately two or three times better than NaI but the largest current size is fifty times smaller than NaI crystals, although this is changing rapidly driven by the needs of academic researchers. Large CdZnTe and LaCl3:Ce or LaBr3:Ce scintillators cannot yet be produced in sufficiently large volumes and will initially find application in small handheld devices.

4 Muon detection

Muon detection is an attractive possible future technique to detect SNM because it exploits a safe, free and ubiquitous source of radiation. Charged muons are produced when very high energy cosmic radiation ($>10^{11}$ GeV) interacts with air molecules in the upper atmosphere. A large amount of the initiating momentum is carried forward resulting in a continuous muon spectrum stretching from 0 to over 1000 GeV at sea level but with an energy intensity peak at around 1GeV.

As muons move through materials, they lose energy and are scattered, accumulating a net deflection around their incident direction. Materials with high atomic number and number density, such as SNM, can be identified by measuring muonic energy loss and scatter angle as muons pass through. A muon detector under development at Los Alamos National Laboratory would place particle detectors above and below a vehicle and record each muon's path before and after it passes through it. Using the path information and muon scattering theory, a computer program could then calculate and display three dimensional images of dense, high atomic number objects in the cargo.

A cheaper and simpler method is to detect energetic X-rays emitted by electrons upon excitation by muons. The high energies of these muonic X-rays enable them to penetrate surrounding materials, and their characteristic energies allow specific elements to be identified. For example, in uranium, these muonic X-rays have energies of nearly 6 MeV, which is a very rare energy signature and so provides a reliable indication of SNM. However, detecting these muonic X-rays requires a gamma ray detector with a sufficiently high efficiency and resolution. Another method is to detect the neutrons and gamma rays produced when negatively charged muons are captured by nuclei since the degree to which muons interact with nuclei increases according to the atomic number of the material.

5 Imaging systems

At energies around several MeV, gamma rays can be used in a radiographic mode to take an image of what is inside a container. The degree to which they are absorbed or penetrate will depend on the atomic number and density of the material. 5MeV gamma rays have an attenuation length in iron of 4.3 inches and can image through 30 inches of steel.

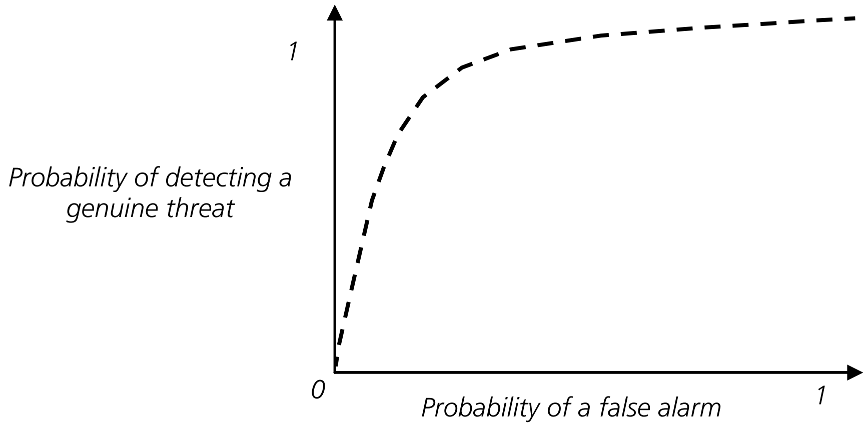
The degree to which neutrons, high energy X-rays, gamma rays or muons penetrate materials depends on the atomic number and density of the material. Imaging systems exploit this property to localise dense materials embedded in less dense materials. The Vehicle and Container Inspection System (VACIS) deployed at the Los Angeles/Long Beach port (among other locations) uses transmission radiography (with MeV gamma rays from a radioactive source, such as cobalt-60) and backscatter X-rays (from a 450kV generator). The radiography source and backscatter system are housed in a truck that drives down the line of containers to be inspected. A boom from the truck extends over the containers with a rack of radiography detectors hanging down the other side. Each container is scanned in approximately one minute. Objects with high atomic numbers within the container are readily detectable and often identifiable.

Gamma radiography produces 2D images of objects and even when these images are superimposed, gamma ray shadows of many objects can prove confusing. Cosmic rays muons have greater penetrative powers than gamma rays and therefore may be used to provide 3D information.

6 Bayesian networks and false alarm rates

One of the major problems encountered in operating all screening systems is the false alarm rate. This can be greatly reduced using a series of independent detection systems, which are combined to form a network. Such networks can be discussed and analysed in terms of a *Bayesian network* (or a *belief* network). This involves a probabilistic graphical model of the network, which represents a set of variables and their probabilistic independencies. Normally, scientific models that allow the introduction of prior knowledge into calculations tend not to be used to prevent the introduction of data that might bias the results. However, there are times, such as the present case of a detection network, where the use of prior knowledge, including information from intelligence gathering, would be a useful addition to the evaluation process. A Bayesian network can make use of such knowledge and Bayesian analysis can be applied since the elements of the screening network are independent.

Figure 1: The Receiver Operator Characteristic (ROC) curve



This is exemplified in the experience of screening for high explosives at airports where false alarm rates can be reduced significantly if detection systems are networked. The Receiver Operator Characteristic (ROC) curve, shown in Figure 1, represents the relationship between the probabilities of detecting a threat and detecting a false alarm. Using Bayesian statistics, the ROC performance of networked systems can be significantly better than that of its individual members. The probability that a system detects a genuine threat depends on the prior probability, based on all previously gathered information, that a threat has been detected. If two systems are connected, then the output of the first system (alarm or clear) allows a new calculation of the prior probability that a threat has been detected or not. This then updates the prior probabilities for the second system. Bayesian analysis shows that the probability of a threat being detected, given that both these two systems sound the alarm, increases. Where the threat probability is low, if detection systems are networked, then the probability that a threat is detected across the whole network increases. Note that this analysis only applies serially to an uncorrelated set of detection systems. Each system needs to have a probability of detecting a threat material and a false alarm rate uncorrelated to the other systems in the network.