Review of current and emerging technologies which use ionising radiation for security inspection purposes.

Defence Science and Technology Laboratory
Environmental Sciences Department

Report Number: DSTL/CR54466/V2

19 April 2011

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Executive summary

The Food Standards Agency (FSA) is considering the extent to which security inspection devices using ionising radiations for the examination of cargo, baggage and packages might come under the scope of the UK regulations for the irradiation of foodstuffs.

The Defence Science and Technology Laboratory (Dstl) has previously conducted two desk studies on behalf of the FSA to examine whether current, or emerging, security inspection technologies using ionising radiation fall under the scope of the Food Irradiation (England) Regulations 2009. These regulations apply to equipment operating above any of the following levels:

- x-rays with energies in excess of 10 MeV;
- neutrons with energies in excess of 14 MeV;
- other radiations with energies in excess of 5 MeV;
- where the absorbed dose due to neutrons exceeds 0.01 Gy;
- where the absorbed dose from radiations other than neutrons exceeds 0.5 Gy.

There is no evidence in the available literature to suggest that radiation outputs from current security screening devices used in the UK exceed the above levels. However, some emerging technologies could exceed these levels. These technologies include linear accelerators for the production of x-rays, gamma generators based on nuclear reactions, compact neutron generators based on fusion reactions and laser-driven accelerators.

This report is an unclassified summary of the two previous desk studies.

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1 Introduction

1.1 The Food Standards Agency (FSA) is considering the extent to which the widespread and increasing use of ionising radiation in security inspection devices might come within the scope of the UK regulations for the irradiation of foodstuffs.

1.2 The Defence Science and Technology Laboratory (Dstl) was tasked by the FSA to carry out two desk studies [1, 2] to provide information on current systems that utilise ionising radiation and likely future developments in this area.

1.3 The first desk study [1] examined three categories of current security screening equipment: cargo screening systems; baggage / explosive detection systems; and mail screening systems. Information on these devices was collated with the aim of verifying that they do not come within the scope of the Food Irradiation (England) Regulations 2009 [3]. These regulations apply to equipment operating above any of the following limits:

- x-rays with energies in excess of 10 MeV;
- neutrons with energies in excess of 14 MeV;
- other radiations with energies in excess of 5 MeV;
- where the absorbed dose due to neutrons exceeds 0.01 Gy;
- where the absorbed dose from radiations other than neutrons exceeds 0.5 Gy.

1.4 The first desk study showed that most of the systems that are in use currently are based on x-ray screening, but that significant effort is being put into developing new technologies for the screening of goods and individuals to combat terrorism and detect contraband. It was recommended that further investigation be carried out into the following areas:

- systems using linear accelerators to produce x-rays;
- recent developments, especially those incorporating sources of neutron radiation;
- systems with computed tomography (CT) functionality or those able to produce three dimensional images.

1.5 The aim of the second desk study [2] was to identify potential future developments in the area of security inspection devices through a programme of horizon scanning, and to assess whether future developments in this area are likely to come within the scope of the Food Irradiation (England) 2009 Regulations [3].

2 Method

2.1 For the first desk study, Dstl used pre-existing knowledge as well as contacts within industry and other government departments to compile a database of current security inspection equipment used in the UK, and their radiation output characteristics.

2.2 Given the legislative framework, there was clearly a need to understand the energy of the delivered radiation and absorbed dose delivered to the item under inspection.

2.3 Eight categories of inspection device were initially identified. However, for the purpose of this study Dstl concentrated on those likely to give rise to the highest radiation dose to the object under inspection: cargo screening systems; baggage / explosive detection systems; and mail screening systems.

2.4 For the second desk study, Dstl initiated an extensive programme of technology watching. This was carried out using the following sources of scientific and technical information: The Web of Science, Science Direct, IEEE Xplore and INSPEC.

2.5 Each source was interrogated using suitable search criteria in order to yield relevant information for emerging technologies in the area of security screening. The search criteria were intentionally broad, with the aim of capturing as much information on relevant emerging technologies as possible, regardless of the specific application in the field of security screening.

2.6 The majority of information retrieved by the literature searches had application, or potential application, in the areas of baggage and cargo interrogation. Over the past few years, developments in the area of security inspection have experienced significant growth and inspection systems are being developed which are able to image large objects such as cargo containers, trains, trucks and boats, using a variety of platforms including fixed installations, gantry units and drive-through portals. The following emerging areas were considered:

- photon interrogation;
- neutron interrogation;
- combined interrogation with photons and neutrons;
- and interrogation methods using other types of radiation.

3 Radiation output characteristics from current inspection equipment

3.1 Regardless of application and equipment type, the radiation used will be emitted either from a source of radioactive material or via electrical equipment such as an x-ray generator.

3.2 Cargo screening systems

3.2.1 Cargo screening systems typically use x-ray or gamma ray sources such as Cs-137 or Co-60, although some use neutron sources. The energy emissions from these sources do not change, however dose delivered to the object under inspection will vary with exposure time.

3.2.2 Systems using conventional x-ray generators typically produce radiation with energies of a few hundred keV. However, systems that use linear accelerators can produce radiation with energies of the order of MeV. The highest found in this study was 9 MeV, although 2.5 MeV is more typical.

3.2.3 The maximum absorbed dose delivered to the object under inspection was 115 µGy per scan. However, manufacturers' data indicates that doses from x-ray and gamma-ray cargo screening systems are typically around 10 µGy per scan.

3.2.4 Two systems were identified that utilise neutron radiation. One was a prototype system called the PFNA and the other was a commercially available security scanner. In the case of the PFNA system, the absorbed dose to object under inspection was 157.5 µGy per scan, compared to 2.5 µGy per scan from the commercially available system.

3.3 Baggage / explosive detection systems

3.3.1 Baggage screening systems typically image objects by passing them slowly through a thin band of x-rays. These systems are available in various sizes; from those used for screening individual items of cabin baggage at airports, to those used for screening hold luggage.

3.3.2 Most modern baggage systems use two different energies of x-ray to enable the discrimination of specific materials of interest. In this way, a colour-coded image is built up where, for example, organic materials may be coloured orange and metallic materials coloured blue. All such baggage x-ray systems are also known as Explosive Detection Systems (EDS).

3.3.3 Some baggage x-ray systems have CT functionality, where a three-dimensional image of the object can be created. Whilst this technology can produce images of greater quality and provide more information about the item of interest, it can potentially lead to an increase in the dose that is delivered to the target.

3.3.4 Obtaining information on the radiation outputs from these types of systems was challenging, perhaps because individuals would not normally be the object under inspection. The limited information available (mostly from manufacturers) indicated that the maximum x-ray energy is 6 MeV, although this is extreme and energies are typically in the range 150-170 keV. The maximum dose delivered to the item under inspection from such equipment was found to be 14 µGy, although 2-3 µGy was more typical.

3.4 Mail screening systems

3.4.1 Mail screening can be conducted by either a traditional conveyor x-ray machine (similar to a small baggage screening system), or a cabinet type fluoroscope.

3.4.2 Typical energies are in the range 60-90 keV, although energies of 160 keV are quoted in some cases.

3.4.3 Manufacturers' data indicate that doses to the target are typically of the order of several µGy. However, in an investigation carried out previously by Dstl a number of thermoluminescent dosemeters were irradiated in a postal fluoroscope. Assessment of the dosemeters indicated that a dose of 2-3 mGy had been received.

4 Radiation output characteristics from future inspection equipment

4.1 The second desk study identified a number of emerging technologies that have potential application in the area of security screening. This report concentrates on those most likely to come within the scope of the Food Irradiation (England) Regulations 2009 [3].

4.2 Photon Interrogation Techniques

4.2.1 Dual-energy X-radiography

4.2.2 Single energy x-rays are particularly effective at detecting hidden objects with readily identifiable shapes such as firearms; however they are poorly suited to detecting low-density organic threats with no defined shape.

4.2.3 Dual-energy x-ray systems are the primary screening method for passenger luggage, as they give information on the composition of objects as well as their shape. In order for the dual-energy technique to work, both energies of radiation must be sufficiently penetrating to be detectable after passing through the target. The screening of large objects such as cargo containers therefore requires x-rays with energies of several MeV. These x-rays are often generated using a linear accelerator.

4.2.4 Commercially available systems typically produce beams of x-rays with energies between 4 and 9 MeV. However, linear accelerators are readily able to deliver x-rays with energies far in excess of those specified in the Food Irradiation (England) Regulations 2009 [3], and energies above 25 MeV are not uncommon. Some of the examined literature suggests definite advantages of interrogation with x-rays in excess of 10 MeV.

4.2.5 The available literature makes no mention of likely doses to the object under inspection. However, the US Department of Homeland Security is currently developing the Cargo Advanced Automated Radiography System (CAARS) for general purpose screening of all cargo containers. Monte Carlo simulations estimate that a whole body dose of around 2 mGy would be received by a stationary human inside the container. This would increase to 20 mGy if the individual traversed the container staying in the beam for the full period of the scan.

4.2.6 Computed Tomography

4.2.7 Since the introduction of x-ray computed tomography (CT) in the 1970s, developments have been driven primarily by requirements for medical applications and there was little reference in the examined literature to the use of x-ray CT for security inspection purposes.

4.2.8 **Pulsed Photo-nuclear Assessment (PPA)**

4.2.9 For over a decade, Idaho National Laboratory, in conjunction with other institutions, has been developing active interrogation techniques based on photo-nuclear reactions. With sponsorship from various authorities, this photon-based interrogation technique has been developed into a prototype, field deployable system that can identify special nuclear material (SNM) in an array of different cargo containers.

4.2.10 The prototype PPA technology can readily produce bursts of accelerated generated x-ray radiation with energies between 2 and 12 MeV.

4.2.11 Due to current food irradiation limits, most studies with this system have been performed at, or below, 10 MeV. While this energy currently applies to cargo inspections, the World Health Organisation (WHO) and the Food and Drug Administration (FDA) have indicated that higher-energy radiation beams could be considered for future operations. Planned enhancements to the PPA system include interrogation with x-ray energies in excess of 10 MeV.

4.2.12 **Nuclear Reaction Based Interrogation**

4.2.13 Compact interrogation sources are being developed that use low-energy nuclear reactions to produce high-energy gamma-rays for security inspection purposes. Gamma-rays with energies up to 18 MeV can be produced from $^{11}B(p,\gamma)\ ^{12}C$ and $^{7}Li(p,\gamma)\ ^{8}Be$ reactions.

4.2.14 The Lawrence Berkeley National Laboratory (LBNL) has designed and built a first generation novel gamma generator capable of producing gamma-rays with energies up to 18 MeV. This gamma generator has potential application in the field of cargo screening, and the project is supported by the US Department of Homeland Security.

4.2.15 The available literature does not give any indication of the typical dose delivered to the object under inspection.

4.3 Neutron Based Interrogation Techniques

4.3.1 X-ray systems have limited ability to distinguish between explosives, drugs and innocuous organic materials. This has stimulated the development of alternative methods for cargo inspection, including those based on neutrons. Neutron radiography can be performed using either fast neutrons (energies of the order of MeV), or thermal neutrons (energies below approximately 0.025 eV). Fast neutron techniques tend to be more attractive for cargo inspection, as fast neutrons are able to penetrate the cargo container.

4.3.2 As neutrons pass through the object under inspection, they may be scattered or captured by atomic nuclei. Scattering can lead to the excitation of atomic nuclei, whilst capture can lead to the formation of new radioactive species (a process known as neutron activation). The products of the scattering and capture may subsequently decay through the emission of characteristic gamma-rays. The scattering and capture reactions provide information about the elemental composition of the object being interrogated, and this enables the detection and identification of explosives, narcotics, toxic agents, SNM and other contraband. It should be noted that the emitted gamma-rays can have high energies, in excess of 10 MeV in some cases.

4.3.3 A number of neutron interrogation systems use neutron generators, based on compact linear accelerators, and produce neutrons by fusing isotopes of hydrogen together. The fusion of two deuterium atoms (D+D) results in the formation of a 2.5 MeV neutron, and fusion of a deuterium and a tritium atom (D+T) results in the formation of a 14.1 MeV neutron. These generators have the advantages that they are available commercially, relatively inexpensive and produce high neutron fluxes. The neutrons are produced through the fusion of hydrogen isotopes and typically have energies of up to 14.1 MeV.

4.3.4 The available literature does not give any indication of the typical dose delivered to an object under inspection.

4.4 Combined Interrogation Using Photons and Neutrons

4.4.1 A recent development in air-cargo scanning is the dual photon-neutron system developed at the Commonwealth Science and Industrial Research Organisation (CSIRO). CSIRO has been working with the Australian Customs Service at Brisbane National Airport to develop an inspection system capable of scanning airfreight containers in 1-2 minutes, without the need to unpack them. This system uses a commercially available neutron generator to produce neutrons with energies of 14.1 MeV, together with a 185 GBq sealed Co-60 gamma source; however, a linear accelerator could readily be used to generate the gamma component.

4.4.2 The manufacturer's data states that the absorbed dose received by an individual in a cargo container during scanning is approximately 2.5 μGy. Residual induced radioactivity in the cargo has been calculated to be 1000 times lower than the natural radioactivity in typical cargo.

4.4.3 It should be noted that combined techniques making use of multiple sources of radiation for interrogation purposes, may increase the dose delivered to the objects under inspection compared to any one of the sources being used in isolation.

4.5 Interrogation Methods Using Other Radiations

4.5.1 Laser-driven plasma accelerators are in use at LBNL and the University of Nebraska. This equipment is readily able to produce high quality electron beams in the energy range 0.1-1 GeV. These devices have a small footprint (around 18 m^2) and their cost, like their size, has reduced considerably over the last five years.

4.5.2 Laboratory studies and simulations show that these high-energy electron beams constitute a promising probe for long range (up to 100m) interrogation of concealed SNM. With continued development, these high-energy electron beams may evolve into compact and potentially portable sources, with applications in a number of areas of security screening.

5 Conclusions

5.1 There is no evidence that any of the security screening systems currently in use in the UK fall under the scope of the Food Irradiation (England) Regulations 2009 [3] on the basis of their ionising radiation output. However, there are a number of emerging systems with components that could fall under the scope of the regulations on the grounds of radiation energy, and these are summarised in the table below.

Developing technology	**Of regulatory concern**	**Energy (MeV)**	**Dose (mGy)**
Linear accelerators	Potentially	2 - 25	2-20‡
Gamma generators based on $^{11}B(p,\gamma)\ ^{12}C$ and $^{7}L(p,\gamma)\ ^{8}C$ reactions	Yes	12 - 18	*
Neutron generators based on the D+T reaction	Yes	14.1	*
Laser-driven accelerators	Yes	> 400	*

* indicates insufficient information to estimate a typical dose.
‡ Estimates based on Monte Carlo simulations for the CAARS.

5.1.1 Systems utilising linear accelerators for the production of x-rays: At present, x-rays are the most commonly used ionising radiation for security inspection purposes; however, x-ray techniques are unable to discriminate between different classes of organic materials. Developments are being made in this field, some of which use linear accelerators to produce x-rays with energies high enough to penetrate large cargo containers, and which would bring such equipment within the scope of reference [3].

5.1.2 Neutron generators: The ability of neutron systems to discriminate between different isotopic compounds gives them a significant advantage over other technologies. Currently, there are no neutron-based techniques in routine use at any airport or shipping ports in the world; however, there is a significant amount of developmental work being carried out in this area. The most commonly used neutron generator produces 14.1 MeV neutrons; therefore security inspection devices employing these generators will come within the scope of the above regulations. Neutron-based interrogation methods intentionally induce activation in the target material, which may result in additional radiation exposure to an object under inspection.

5.1.3 Gamma generators: LBNL has developed a novel gamma generator for cargo screening applications. These high-energy gamma generators produce gamma-rays up to 18 MeV.

Any security inspection device using these gamma generators will come within the scope of the UK Food Irradiation Regulations.

5.1.4 Laser-driven accelerators: Laboratory studies and simulations have indicated that electron beams constitute a promising probe for the detection of SNM in cargo containers. The laser-driven accelerators that are used to generate these beams have shrunk several-fold in cost and size over the last five years, and are readily able to produce electron beams far in excess of the limits detailed in reference [3].

5.2 Due to the novel and developmental nature of the technologies investigated, there is a lack of dosimetric data in the published literature. It has therefore not been possible to compare the doses generated by most of these new techniques to the levels detailed in reference [3]. Where doses to the object under inspection have been identified, they have been found to be several orders of magnitude below regulatory concern.

6 Recommendations

6.1 Dstl recommends the following:

6.2 a watching brief is maintained on international recommendations from the WHO and FDA;

6.3 a watching brief is maintained on all developing technologies in the area of security screening;

6.4 as new security screening technologies are introduced across the world, technical and dosimetric data is collected to better inform the FSA.

7 List of References

[1] Review of current security inspection devices that utilise ionising radiation. Defence Science and Technology Laboratory, report number DSTL/CR47305.

[2] Review of emerging technologies which use ionising radiation for security inspection purposes. Defence Science and Technology Laboratory, report number DSTL/CR51960.

[3] The Food Irradiation (England) Regulations 2009, (2009 SI 1584), Her Majesty's Stationery Office.

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3. Title of Report Review of current and emerging technologies which use ionising radiation for security inspection purposes**.**		
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5. Authors Defence Science and Technology Laboratory, Environmental Sciences Department		
6. Originator's Name and Address Environmental Sciences Department Dstl Porton Down Salisbury Wiltshire, SP04 0JQ	7. MOD Sponsor Name and Address	
8. MOD Contract number and period covered		
9. Other Report Nos. DSTL/CR47305, DSTL/CR51960		
10. Date of Issue 19/04/2011	11. Pagination 18 pages	12. No. of References 3
13. Abstract (A brief (approximately 150 words) factual summary of the report) Dstl has previously conducted two desk studies on behalf of the FSA to examine whether current, or emerging, security inspection technologies using ionising radiation fall under the scope of the Food Irradiation (England) Regulations 2009. There is no evidence in the available literature to suggest that radiation outputs from current security screening devices used in the UK exceed the above levels. However, some emerging technologies could exceed these levels. These technologies include linear accelerators for the production of x-rays, gamma generators, compact neutron generators and laser-driven accelerators. This report is an unclassified summary of the two previous desk studies.		
14. Abstract Protective Marking including any Caveats UNCLASSIFIED		
15. Keywords/Descriptors (Authors may provide terms or short phrases which identify concisely the technical concepts, platforms, systems etc. covered in the report. Security scanners, food irradiation, x-rays, neutrons, linear accelerators, CT, cargo, baggage.		

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