Paper

RADIATION DOSE EQUIVALENT TO STOWAWAYS IN VEHICLES

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Abstract—The U.S. Bureau of Customs and Border Protection has deployed a large number of non-intrusive inspection (NII) systems at land border crossings and seaports throughout the United States to inspect cars, trucks, and sea containers. These NII systems use x rays and gamma rays for the detection of contraband. Unfortunately, undocumented aliens infrequently stow away in these same conveyances to illegally enter the United States. It is extremely important that the radiation dose equivalent imparted to these stowaways be within acceptable limits. This paper discusses the issues involved and describes a protocol the U.S. Bureau of Customs and Border Protection has used in a study to measure and document these levels. The results of this study show that the radiation dose equivalent to the stowaways from the deployed NII systems is negligibly small and does not pose a health hazard.
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Key words: dose equivalent; exposure, radiation; gamma radiation; x rays

INTRODUCTION

THE U.S. Bureau of Customs and Border Protection (BCBP) has deployed a variety of non-intrusive inspection (NII) systems along the borders with Mexico and Canada and at seaports. These NII systems assist the customs inspectors in their task of examining the trucks, tractor-trailers, and cargo containers entering the United States for contraband such as illegal drugs and explosives. By increasing the speed and accuracy of examinations these systems also facilitate the movement of cargo through the ports.

The existing NII systems use x rays and gamma rays for the detection of contraband. The detection is based on the shape, size, and density of the contraband in the radiographic image as produced by the NII system. A prototype NII system based on pulsed fast neutron analysis (PFNA), which uses neutrons for the interrogation of the cargo and claims to identify the contraband, will be tested in the near future at El Paso, TX.

Since cases of stowaways, or undocumented aliens, have been reported in vehicles that are subject to inspection, it is important to determine the radiation dose equivalent that they might potentially receive. For this reason an anthropomorphic (i.e., a tissue equivalent standard reference human) phantom was borrowed from the National Institute of Health (NIH) in Bethesda, MD, to use with the NII systems.

Another important reason for undertaking this effort was to verify the dose modeling calculations generated by a report (GSA 2001). This report stated that the dose equivalent to an undocumented alien is greater when he or she is lying down than when he or she is standing inside the cargo container being examined by the prototype PFNA system. This was disputed by a number of radiation safety experts. They contended that the radiation dose is the same regardless of posture of the stowaway inside the cargo container.

The following NII systems, deployed by BCBP at various ports of entry, were utilized during the first two months of 2001 in the study to collect the dosimetry information:

1. Truck x-ray (TXR) system;
2. Mobile truck x ray—wide eye (MTXR-WE) system;
3. Mobile truck x ray—low under carriage (MTXR-LUV) system;
4. Vehicle and cargo inspection system (VACIS-II);
5. Mobile truck gamma-ray (MTGR) system;
6. Railroad inspection (RailVACIS) system; and
7. Container x ray—6 MeV (CXR-6M) system.

In addition to these systems, radiation dose equivalent to the phantom was measured in open air inside the prototype PFNA system at the developer's facility in California.

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DESCRIPTION OF HUMAN PHANTOM

The male human phantom, called RANDO MAN by the manufacturer (Nuclear Associates, 100 Voice Road, Carle Place, NY 11414-0349), represents a 175 cm (5 feet 9 inches) tall and 73.5 kg (162 lb) male figure. This phantom is constructed with a natural human skeleton, which is cast inside soft tissue simulating material. The human skeletons are not the same size and shape as the mold used by the manufacturer. Also, they reflect human characteristics such as lack of symmetry and distorted joints. For this reason, the technicians have to reconstruct the skeleton by making minor adjustments to facilitate the positioning of the skeleton within the mold. In addition, lungs are molded to fit the contours of the natural rib cage. Also, care is taken to replicate the air spaces of the head, neck, and stem bronchi.

The phantom is made with two tissue-simulating materials: a soft tissue material to simulate muscle tissue and another material to simulate lung material. Both are designed to have the same absorption (hence radiation dose) as human tissue at normal radiotherapy exposure levels. The soft tissue, which simulates the muscle tissue, is made from a proprietary urethane formulation. This material has an effective atomic number and mass density that simulates muscle tissue with randomly distributed fat. The simulated lung material has the same effective atomic number as the soft tissue material, with a density that simulates the lung in the median respiratory state.

The torso of the phantom is constructed in sections. Each section has registration pins mounted inside to facilitate proper alignment. An assembly unit consisting of four rods and two plates holds the entire phantom together. For the test, the assembly was encased in a close fitting box made with pieces of wood screwed together.

The phantom materials are radioequivalent to (behave the same way as) the corresponding human materials for x rays, gamma rays, and neutrons. These materials are matched to the human tissue with respect to the effective atomic number, which is required for low-energy equivalence. They are also matched to the density, which is required for high-energy equivalence.

The phantom used in the testing did not have arms and legs. The phantom was placed either on the floor (reclining position) or on the stack of five pallets (standing position). These pallets were necessary to raise the head of the phantom to a height of about 1.75 m (5 feet 9 inches). A picture of the phantom is shown in Fig. 1, and the elemental composition and other pertinent information supplied by the manufacturer is given in Table 1.

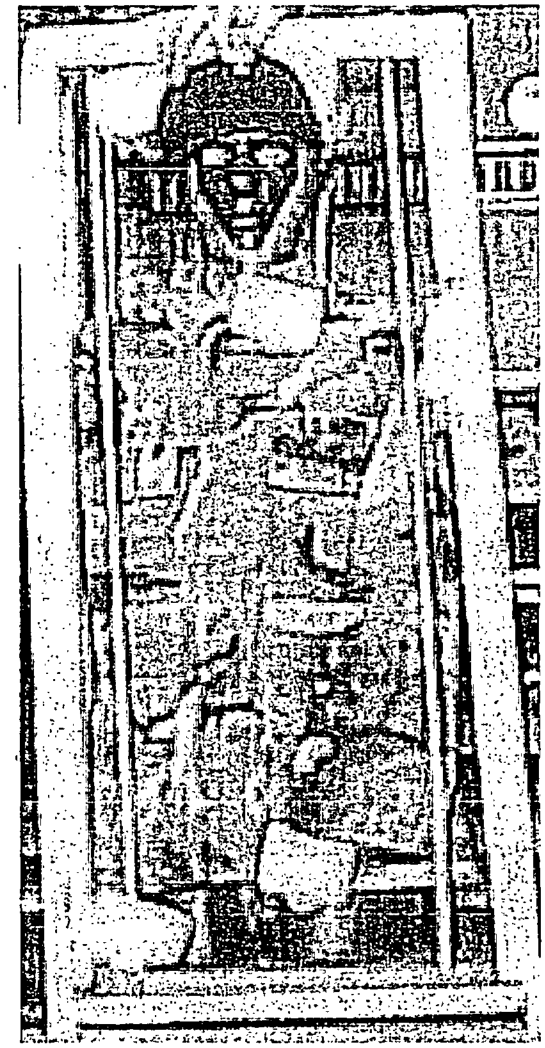

Fig. 1. Human phantom in its box.

Table 1. Elemental composition and physical data of the material used in RANDO MAN phantom.

Elemental composition	
Element	Weight %
Carbon	67.78
Oxygen	20.31
Hydrogen	9.18
Nitrogen	2.50
Antimony	0.22
TOTAL	99.99
Other physical data	
Effective atomic number	7.60
Electron density	3.2781×10^{26} e kg^{-1}
Mass density	997 kg m^{-3}

DESCRIPTION OF NII SYSTEMS

Truck x-ray (TXR) system

This system (Fig. 2) uses two x-ray sources and the corresponding transmission, backscatter, and sidescatter

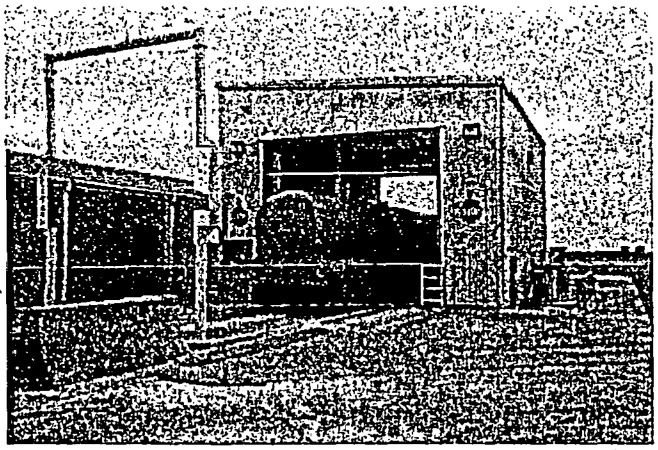

Fig. 2. Truck x-ray (TXR) system.

Fig. 3. Mobile truck x ray—wide eye (MTXR-WE) system.

detectors. The transmission detectors are L-shaped to completely intercept the x rays from the source. These are housed inside a structure, which looks like a car wash. The x-ray sources are located in pits below ground level such that the radiation beam is pointed upwards and at an angle of 0.175 radian (10 degrees) from the direction of travel of the truck which is being pulled through the structure on a conveyer system. The narrow (pencil-like) beams produced by a chopper wheel are swept upward through an arc of 0.750 rad (43 degrees).

The overall facility dimensions are length (from entrance barrier to the end of exit ramp), 43.28 m (142 feet); width (structure plus walkways), 12.80 m (42 feet); and height (of structure), 7.62 m (25 feet). It is designed to inspect vehicles that are 21.34 m (70 feet) long, 2.59 m (8.5 feet) wide, 4.66 m (15.3 feet) high and weigh up to 36,287 kg (80,000 pounds). Normal settings for the x-ray sources are 450 kVp operating with a tube current of 10 mA. The normal scan speed is 9.45 m (31 feet) min^{-1}. The dose rate at 1 m from the slit is 0.30 Gy (30 rad) min^{-1}.

Mobile truck x ray—wide eye (MTXR-WE) system

This system (Fig. 3) is mounted on a truck and scans a parked vehicle as it moves past it at slow speed. It uses a single 450 kVp x-ray generator operating at a nominal current of 6.6 mA. The horizontal portion of the transmission detector is attached to the horizontal arm of the boom, and the vertical portion is mounted at the end of the boom and hangs from it. The backscatter detectors are located on both sides of the aperture from which the x rays are being emitted in the form of pencil beams from a rotating wheel. The system has two scan speeds: slow, 8.26 cm (3.25 inches) s^{-1}, and fast, 16.51 cm (6.5 inches) s^{-1}. The dose rate at 1 m from the slit is 0.20 Gy (20 rad) min^{-1}.

Mobile truck x ray—low under carriage (MTXR-LUV) system

This inspection system (Fig. 4) scans a parked truck as it moves past it. X rays from a generator operating at 420 kVp and 10 mA form transmission and backscatter images of the truck. The center of the x-ray source is about 50.8 cm (20 inches) from the ground. The distance between the side of the MTXR-LUV truck and the detector array is exactly 3.66 m (12 feet), and the 2.59 m (8.5 feet) wide truck to be examined is parked in such a way that there is clearance of 53.34 cm (21 inches) on both sides. The fan beam spans 1.4 rad (80 degrees) vertically and 0.350 rad (20 degrees) horizontally and strikes the truck with an oblique angle of 0.175 rad (10 degrees). The dose rate at 1 m from the slit is 0.21 Gy (21 rad) min^{-1}. (This system is no longer being used by BCBP.)

Vehicle and cargo inspection system (VACIS-II)

This relocatable inspection system (Fig. 5) uses 662 keV gamma rays from a 37 GBq (1 Ci) ^{137}Cs sealed radioactive source and a vertical array of 336 sodium iodide detectors to form an image of a truck. [These

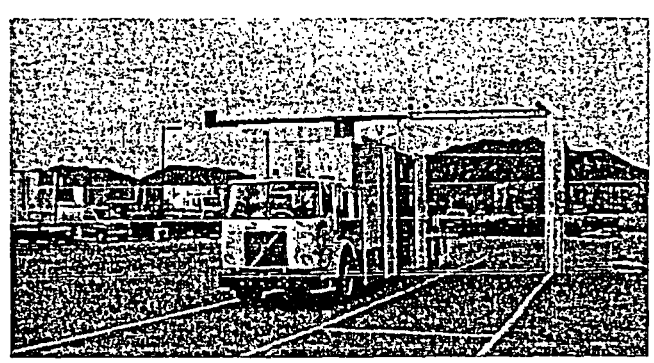

Fig. 4. Mobile truck x ray—low under carriage (MTXR-LUV) system.

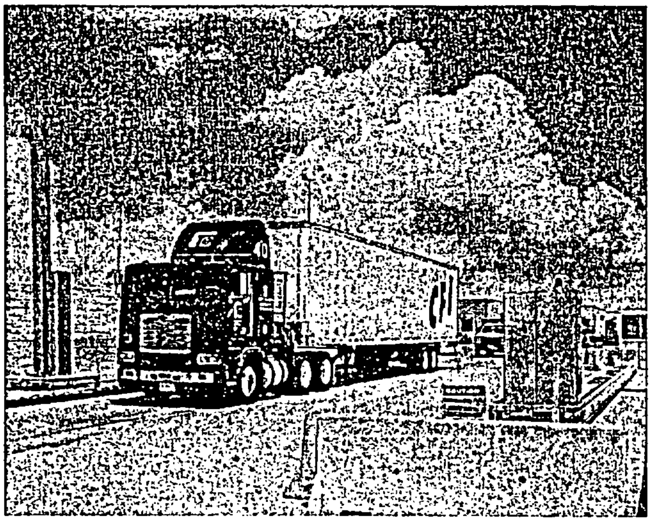

Fig. 5. Vehicle and cargo inspection system (VACIS-II).

systems are being retrofitted to use 18.5–37.0 GBq (0.5–1.0 Ci) ^{60}Co sources, which emit 1.17 and 1.33 MeV gamma rays, to obtain better penetration through dense cargo.] The source and detector trolleys move in synchronization along two parallel 27.43 m (90 feet) long tracks to complete a scan in 75 s. The source track is 1.22 m (4 feet) wide and the detector track is 1.83 m (6 feet) wide and both are placed in a relatively flat area (such as a parking lot) about 10.67 m (35 feet) apart with the truck to be examined parked between the two tracks.

An operator's booth, which is used as a command and control center, is placed nearby but outside the radiation safety exclusion zone. The effective (time-averaged) dose equivalent rate is 0.5 μSv (50 microrem) h^{-1} at the boundary of the radiation safety exclusion zone (Khan 1996). Additional space is required for the trucks to approach the inspection area and to exit from it.

An electrically actuated secondary shutter mechanism is attached to the steel and tungsten source housing. This enables the beam to be turned on and off within a fraction of a second. In addition, the gamma rays are restricted to a fan beam that spans 0.611 rad (35 degrees) vertically and 0.087 rad (5 degrees) horizontally. The system is capable of doing oblique scans at 0.175 and 0.350 rad (10 and 20 degrees), and the source height can be adjusted from 76.2 cm (30 inches) to 165.1 cm (65 inches) above ground. The dose rates at 1 m from the 37 GBq (1 Ci) ^{137}Cs and 18.5 GBq (0.5 Ci) ^{60}Co sources are 53 μGy (5.3 mrad) min^{-1} and 107 μGy (10.7 mrad) min^{-1}, respectively.

Mobile truck gamma-ray (MTGR) system

This system (Fig. 6) uses 662 keV gamma rays from a 59.2 GBq (1.6 Ci) ^{137}Cs source to obtain the images of the interiors of vehicles such as trucks, vans, and passenger cars. This system is also known as MobileVACIS. [These systems are being retrofitted to use 37 GBq (1.0 Ci) ^{60}Co sources, which emit 1.17 and 1.33 MeV gamma rays, to obtain better penetration through dense cargo.] It can also be used to scan cargo containers. When not in operation, the source in its tungsten housing and the detector tower are stowed in the back of the truck. It uses a hydraulic lift mounted in the truck to move the gamma ray source housing and the detector tower in position for operation. The detector tower contains a vertical array of 240 sodium iodide detectors. The width of the system in its deployed configuration is 9.34 m (31 feet). The minimum and maximum distances between the source and the detector tower are 4.27 and 6.86 m (14 and 22.5 feet), respectively. Maximum clearance is 5.33 m (17.5 feet). The source housing can be raised and lowered, as required, to obtain the best possible image of the vehicle being scanned.

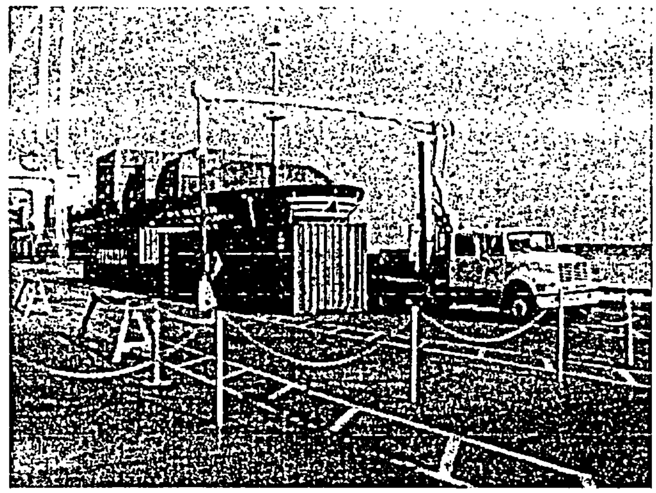

Fig. 6. Mobile truck gamma-ray (MTGR) system.

The source housing produces a narrow beam of gamma rays that strike the detector tower at an oblique angle of 0.175 rad (10 degrees). The fan beam of gamma rays spans an angle of 1.047 rad (60 degrees) vertically. Both stationary (MTGR system stands still and the target vehicle moves between the source housing and the detector tower) and moving (MTGR system is driven past the target vehicle parked between the source housing and the detector tower) scans can be obtained with this system. The optimum speed for both scans is 8.05 km h^{-1} (5 mph).

The minimum side clearance between the side of the vehicle and source is two feet. The source height can be adjusted from the minimum of 15.24 cm (6 inches) from the ground (as measured from the bottom of the housing) to the maximum of 147.32 cm (58 inches) from the ground. The dose rates at 1 m from the 59.2 GBq (1.6 Ci) ^{137}Cs and 37 GBq (1.0 Ci) ^{60}Co sources are 85 μGy (8.5 mrad) min^{-1} and 213 μGy (21.3 mrad) min^{-1}, respectively.

Railroad inspection (RailVACIS) system

This system (Fig. 7) uses 662 keV gamma rays from a 74 GBq (2 Ci) ^{137}Cs source in its steel and tungsten housing and a vertical array of 224 sodium iodide detectors to form an image of rail cars passing by at speeds of 3–8 km h^{-1} (2–5 miles h^{-1}). [These systems are being retrofitted to use 37 GBq (1.0 Ci) ^{60}Co sources, which emit 1.17 and 1.33 MeV gamma rays, to obtain better penetration through dense cargo.] The source housing in its cabinet and the detector tower are about 35 feet apart and fixed in the ground with the railroad tracks running between them. The line joining the source housing and detector tower is at 0.175 rad (10 degrees) with respect to a line perpendicular to the track. This system also uses an electrically actuated secondary shutter to increase shutter speed and to narrow the beam further. The width of the beam when it reaches the detector tower is about 0.91 m (36 inches). The dose rates at 1 m from the 74 GBq (2 Ci) ^{137}Cs and 37 GBq (1.0 Ci) ^{60}Co sources are 107 μGy (10.7 mrad) min^{-1} and 213 μGy (21.3 mrad) min^{-1}, respectively.

Mobile container x ray—MeV (CXR-6M) system

This system (Fig. 8) is a self-powered mobile x-ray system for cargo container inspection. Basically it is a straddle carrier which has been modified to deploy an x-ray imaging system. It comes with an optional supplemental shielding vehicle. The x-ray source is a linear electron accelerator (Linac), which can be operated with two energy settings: low energy (2 MeV) and high energy (6 MeV).

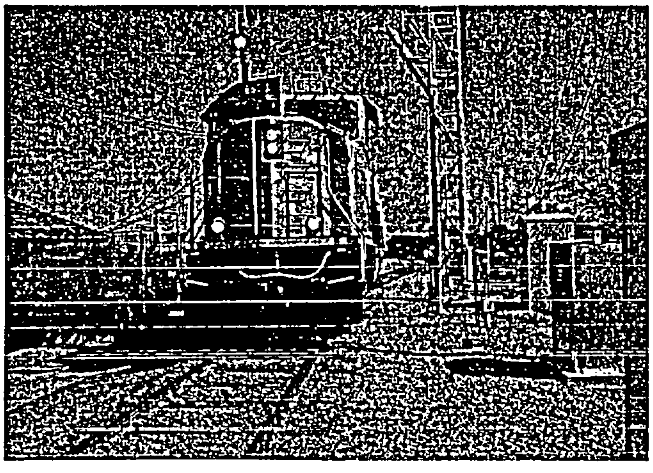

Fig. 7. Railroad inspection (RailVACIS) system.

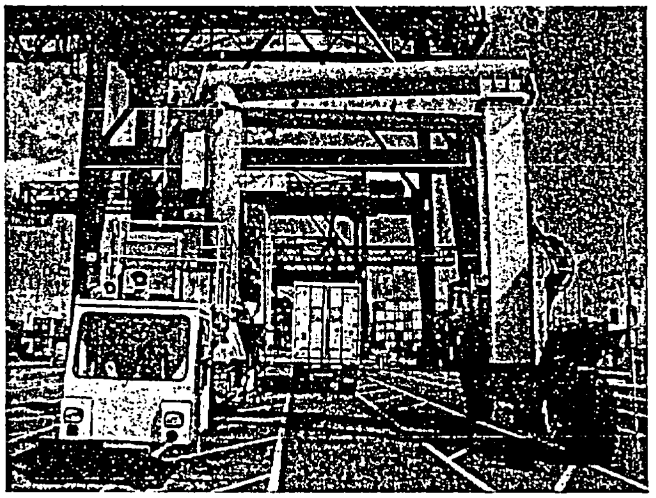

Fig. 8. Container x ray—6 MeV (CXR-6M) system.

The Linac produces short bursts of x rays which last approximately 3 to 4 microseconds with a variable pulse repetition rate ranging from 30 pulses per second (pps) to 300 pps. The dose rates at 1 m due to each pulse from the source are 8.3 mGy min^{-1} (0.83 rad min^{-1}) and 16.7 mGy min^{-1} (1.67 rad min^{-1}) when operating at low and high energies, respectively. The dose rate can be controlled by varying the pulse rate. The respective dose rates for low and high energies are 250 mGy min^{-1} (25 rads min^{-1}) and 500 mGy min^{-1} (50 rads min^{-1}) when operating at 30 pps.

The x-ray beam has a width of 0.254 cm (0.1 inch) as it leaves the Linac, and its width is 3.175 cm (1.25 inch) as it arrives at the detector. This fan beam spans an angle of 0.663 rad (38 degrees), and its bottom edge is parallel to and 38.1 cm (15 inches) above the ground. The height of the fan beam at the detector is 3.69 m (12.1 feet). The fan beam makes an angle of 0.175 (10 degrees) with a line at right angles to the travel direction. The source height can be adjusted from a minimum of 10.16 cm (4 inches) to a maximum 4.27 m (168 inches) above ground, as measured from its bottom. The distance from the source to the detector tower is 4.27 m (14 feet), which leaves clearances of about three feet on either side of the cargo container being examined.

Pulsed fast neutron analysis (PFNA) system

This system (Fig. 9) uses a collimated, pulsed beam of neutrons to determine the location and elemental composition of objects in a truck or cargo container. The radiation source for this system is the (d,d) reaction in a cell that is placed at the end of a mechanical arm capable of vertical movement. The (d,d) reaction produces 8 MeV neutrons and gamma rays (called flash gamma rays). The pulsed width of the neutrons is 1 nanosecond

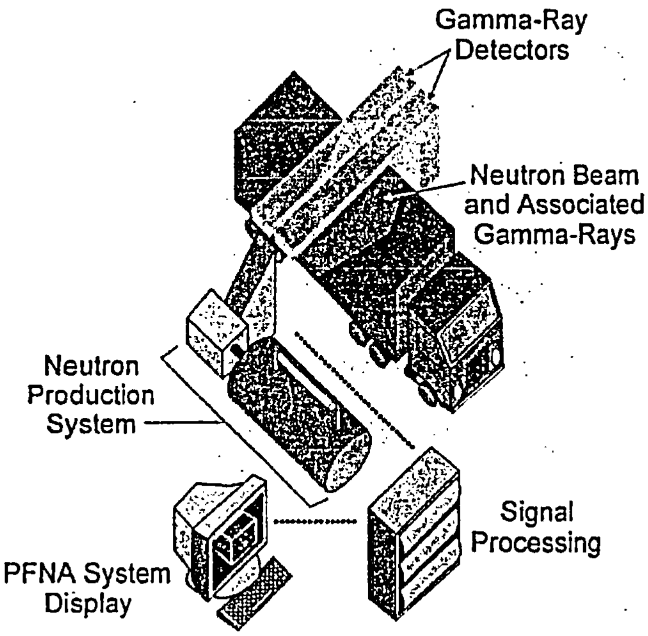

Fig. 9. Pulsed fast neutron analysis (PFNA) system.

and the neutron flux is approximately 1×10^7 cm^{-2} s^{-1} at 1 m from the source.

The neutrons excite the nuclei of the atoms in the object, which then emit gamma rays characteristic of the elements in the object (inelastic scattering). The collimation determines the direction of the beam, defining a path through the truck or container. The position of the object along this path is then determined by a measurement of the time difference between the emission of the neutrons and the detection of the inelastically scattered gamma rays. Since the neutrons move with a known velocity, the time measurement uniquely determines the distance along the neutron flight path, locating the object within the container. By scanning the side of the container with the neutron beam, a three-dimensional image of the contents of the container, including their elemental composition, can be obtained. During the last few years, this basic concept has been supplemented with the addition of neutron and gamma flash radiography.

TEST PROCEDURE

The phantom was placed in vehicles to simulate a stowaway hiding inside in the following positions:

- P1 = Standing, next to wall;
- P2 = Standing, in centerline of vehicle;
- P3 = Reclining, next to wall; and
- P4 = Reclining, in centerline of vehicle.

Luxel badges (Landauer Inc., 2 Science Road, Glenwood, IL 60425-1586), utilizing the principle of optically stimulated luminescence (OSL) for dosimetry, were placed on the upper (chest) and lower (gonad) portions of the torso of the human phantom. Since the lowest sensitivity of Luxel (OSL) badges is 0.01 mSv (1 millirem), the readings from these badges were reported by Landauer, the badge reading service, as M, meaning all readings were below 0.01 mSv (1 millirem).

The Victoreen 450P (Syncor Radiation Management Inc., 6045 Cochran Road, Cleveland, OH 44139) ionization chamber instrument was placed next to the phantom either on the floor (reclining position) or on the stack of five pallets (standing position). As mentioned earlier, these pallets were necessary to raise the head of the phantom to a height of about 1.75 m (5 feet 9 inches). In each case the phantom was placed in the center of the vehicle facing the source of radiation with no cargo present.

The vehicles used for the test consisted of a 12.19-m (40-foot) cargo container (CXR system), a railcar (Rail-VACIS), and a standard size truck (all others). Each vehicle was scanned several times by the NII systems to obtain an average dose received by the phantom.

TEST RESULTS

Truck x-ray (TXR) system

The source settings for the TXR system were 450 kVp, 10 mA, and the x-ray beam was focused at 1.28 m (4.2 feet). It took about half an hour for each pass through the system (including 10 min for the pull through the system and 2 min for the actual scan) because the truck containing the phantom had to wait in line to be inspected. For this reason, three scans were made with the phantom in position P1 (standing next to the wall nearest the control room) and one scan was made in position P3 (reclining next to the wall nearest the control room). No measurements were made with the phantom in the P2 (standing, centerline) and P4 (reclining, centerline) positions.

The average of the three readings from the Victoreen 450P for position P1 was 0.4 μSv (40 microrems) after subtracting the background and the net dose equivalent reading for the position P3 was 0.38 μSv (38 microrems) per scan. The Victoreen was placed on top of the stack of pallets next to the phantom in position P1 and on the floor next to the phantom in position P3.

Mobile truck x-ray—wide eye (MTXR-WE) system

The source settings for the MTXR-WE system were 450 kVp, 6.6 mA, and the beam focus was at 0.98 m (3.2 feet). The fan beam spans 1.274 rad (73 degrees): 0.663 rad (38 degrees) above the horizontal and 0.611 rad (35 degrees) below it. The distance between the side of the

MTXR and truck containing the phantom was 0.91 m (3 feet). The actual scan time was 60 s. Six scans were made for each of the four positions (P1, standing next to wall facing the source; P2, standing on centerline of truck; P3, reclining next to wall facing the source; and P4, reclining on centerline of truck). The net average dose equivalent readings from the Victoreen 450P for the respective positions were 0.53, 0.27, 0.32, and 0.285 μSv (53, 27, 32, and 28.5 microrems) per scan.

Mobile truck x-ray—low under carriage (MTXR-LUV) system

The source settings for the MTXR-LUV system were 420 kVp, 10 mA, and the 1.74 rad (100 degrees) fan beam was at 0.175 rad (10 degrees) from the normal (the line at right angles to the direction of motion). The center of the front of the x-ray source was 6.71 m (22 feet) from the ground and the distance between the side of MTXR-LUV system, and the truck containing the phantom was 0.61 m (2 feet). Each scan took 58 s.

Six scans of each of the four positions (P1, standing next to wall facing the source; P2, standing on centerline of truck; P3, reclining next to wall facing the source; and P4, reclining on centerline of truck) were made. The net average dose equivalent readings from the Victoreen 450P for the respective positions were up to 0.016, 0.009, 0.017, and 0.003 mSv (1.6, 0.9, 1.7, and 0.3 millirems) per scan. The results of the Luxel (OSL) badges readings from Landauer (corrected for background) are shown in Table 2.

Vehicle and cargo inspection system (VACIS-II)

The VACIS-II used a 37 GBq (1 Ci) ^{137}Cs source that emits 662 keV gamma rays. The distance between the source and the side of the truck containing the phantom was 6.71 m (22 feet). Two passes were made with the phantom in position P1 (standing next to wall) and four passes were made with the phantom in position P3 (reclining facing the wall). The total times for the two types of passes were 3 and 6 min. The actual time for a single scan in each case was 60 s.

The background dose equivalent reading during this test was 0.20 μSv (20 microrems) h^{-1}. Taking this into consideration the net average dose equivalent readings from the Victoreen 450P were 0.0475 and 0.05 μSv (4.75 and 5 microrems) per scan, respectively, for phantom positions P1 and P3.

Table 2. Luxel (OSL) badge readings for MTXR-LUV system.[a]

Position	Total reading in mSv for six scans	Average of the higher reading in mSv per scan
P1-Chest	0.14	0.023
P1-Gonad	0.06	
P2-Chest	0.06	0.01
P2-Gonad	0.04	
P3-Chest	0.11	
P3-Gonad	0.12	0.02
P4-Chest	0.07	0.012
P4-Gonad	0.02	

[a] Note: two badges were used on the phantom for each position inside the truck: one on the chest just below the collarbone and the other below the belt line of the torso. The phantom was always facing the source of radiation.

Mobile truck gamma-ray (MTGR) system

The MTGR system (MobileVACIS) used a 59.2 GBq (1.6 Ci) ^{137}Cs source that emits 662 keV gamma rays. The distance from the source to the wall of the truck containing the phantom was 2.54 m (100 inches). The source to detector distance was 6.50 m (256 inches), and the source was 0.91 m (36 inches) above ground. The time for a single scan was 30 s, and six scans for each of the four positions of the phantom inside the truck were made. The net average values of the dose equivalent readings from the Victoreen 450P for positions P1, P2, P3, and P4 were 0.04, 0.42, 0.033, and 0.013 μSv (4.0, 4.2, 3.3, and 1.3 micorems) per scan, respectively.

Railroad inspection (RailVACIS) system

The RailVACIS used a 74 GBq (2 Ci) ^{137}Cs source that emits 662 keV gamma rays. The distance from the source to the wall of the railcar was 5.18 m (17 feet). The walls of the railcar consisted of 0.953 cm (⅜ inch) steel with a lining of 1.27 cm (½ inch) plywood. Six scans were made with the phantom in positions P1 and P3. The net average dose equivalent readings from the Victoreen 450P for the two positions (P1 and P3) were 0.025 and 0.02 μSv (2.5 and 2.0 microrems) per scan, respectively.

Container x ray—6 MeV (CXR-6M) system

Two energy settings were used with the CXR-6M system: high (HI) energy, which was nominally 6 MeV, and low (LO) energy, which was nominally 2 MeV. The system was operating with 30 pulses s^{-1}. According to the manufacturer of the Linac (HI-RAD) the dose rate at one meter from the source slit at HI and LO energy settings is 500 and 250 mGy (50 and 25 rads) min^{-1} or 30 and 15 Gy (3,000 and 1,500 rads) h^{-1}, respectively.

A 12.19 m (forty-foot) cargo container was used to place the phantom in the four positions (P1, P2, P3, and P4) as described before. The source was 1.52 m (5 feet) above ground and 0.91 m (3 feet) from the cargo container wall. The source to detector distance was 4.42 m (14.5 feet) at an angle of 0.175 rad (10 degrees). The speed of the CXR as it scanned the cargo container was 0.81 km h^{-1} (0.5 mph).

Readings at selected positions were obtained with the Victoreen 450P. The measurements for ten scans are given Table 3. The results of the Luxel (OSL) badges readings from Landauer (corrected for background) are shown in Table 4.

Pulsed fast neutron analysis (PFNA) system

The average accelerator current was 70 microamps, and the cell pressure was 130 kPa (18.9 psig). This gave an approximate neutron flux of 1×10^7 cm^{-2} s^{-1} at 1 m from the (d,d) reaction cell.

The phantom was placed (facing the source of radiation) on top of a platform, which moved in front of the rotating arm at a constant speed of 1 cm per second. The distance between the front of the phantom and the source was 2.06 m (6.76 feet).

Dosimetry measurements with the PFNA system were taken in a modified Federal Aviation Administration (FAA) configuration to allow inspection of aircraft cargo containers. The results of the Luxel (OSL) badges readings (neutrons and gammas) from Landauer (corrected for background) and readings from the Victoreen 450P (gamma only) are shown in Table 5.

DISCUSSION OF RESULTS

Comparison of radiation dose equivalents received by phantom in different modalities

The test results presented indicate that the doses to the human phantom from a single scan fall in two categories. The dose equivalent from the gamma ray imaging systems (VACIS-II, MobileVACIS and RailVACIS) and TXR and MTXR-WE systems is of the order of tens of nSv (microrems) and that from MTXR-LUV, CXR, and PFNA systems is of the order of tens of μSv (millirems).

This is clearly shown in Table 6 below, which compares the dose equivalents for a single scan as determined with the Victoreen 450P ionization chamber. These measurements show that the dose equivalents for a single scan range from 25 nSv (2.5 microrems) for RailVACIS to 530 nSv (53 microrems) for MTXR-WE system.

Table 3. Victoreen 450P measurements for CXR-6M system.

Position and energy	Dose equivalent for ten scans, mSv	Dose equivalent for a single scan, mSv
Standing, next-to-wall, high energy	0.21	0.021
Standing, centerline, high energy	0.22	0.022
Reclining, next-to-wall, high energy	0.21	0.021
Standing centerline, low energy	0.169	0.0169
Reclining, centerline, low energy	0.172	0.0172

Table 4. Luxel (OSL) badge readings for CXR-6M system.[a]

Position and energy setting and location of badge	Total reading in mSv for ten scans	Average of the higher reading in mSv per scan
P1-HI-Chest	1.13	0.113
P1-HI-Gonad	0.68	
P1-LO-Chest	0.73	0.073
P1-LO-Gonad	0.47	
P2-LO-Chest	0.28	
P2-LO-Gonad	0.40	0.04
P2-HI-Chest	0.47	
P2-HI-Gonad	0.67	0.067
P3-LO-Chest	0.77	0.077
P3-LO-Gonad	0.71	
P3-HI-Chest	0.115	0.0115
P3-HI-Gonad	0.115	0.0115
P4-LO-Chest	0.25	
P4-LO-Gonad	0.27	0.027
P4-HI-Chest	0.41	
P4-HI-Gonad	0.43	0.043

[a] Note: two badges were used on the phantom for each position inside the truck: one on the chest just below the collarbone and the other below the belt line of the torso. The phantom was always facing the source of radiation.

The ^{60}Co source had not been installed in the gamma ray imaging systems at the time the dosimetry measurements were made. However, it is easy to calculate the potential dose equivalent from the ^{60}Co for each system or modality since the specific gamma ray constant for ^{60}Co is four times that for ^{137}Cs (1.28 vs. 0.32 in units of R m^2 h^{-1} Ci^{-1}). The single scan dose equivalent values for the P1 position for VACIS-II, MTGR system (MobileVACIS) and RailVACIS using ^{60}Co are 100–200, 100, and 50 nSv (10–20, 10, and 5 microrems), respectively.

Table 7 compares the dose equivalents to the phantom for a single scan as reported by Landauer for Luxel badges. PFNA system data is the sum of neutron and gamma ray (N+G) dose equivalents. All others are either x ray or gamma ray as the case may be.

For the PFNA system the dosimetry measurements were taken in the modified Federal Aviation Administration (FAA) configuration and have been multiplied by a factor of 1.43 to obtain the corresponding values for the proposed field test configuration. In all cases, the highest dose equivalents are being used to represent the worst-case scenario.

The dose equivalents to the phantom are very close in value for the standing and reclining positions (next to the wall). Any differences in these quantities for the standing and reclining positions (centerline) can be attributed to various types of shielding materials in path of the beam as it reaches the source, the beam width at the object, and the speed of the scan. Such a calculation was indeed performed for the VACIS-I (Khan 1996), the first prototype system, and the answer was 5 microrems

Table 5. Luxel (OSL) badge readings and Victoreen 450P measurements for PFNA system.

Position of phantom and location of badge	Number of scans	Neutron dose equivalent (Luxel), mSv	Gamma dose equivalent (Luxel), mSv	Luxel N + G per scan, mSv	Gamma dose equivalent (450P), mSv
P1-Chest		2.10	0.10	0.22	
	10				0.17
P1-Gonad		1.50	0.10		
P2-Chest		0.60	0.02		
	7				0.072
P2-Gonad		0.80	0.02	0.12	
P3-Chest		1.10	0.06		
	10				0.138
P3-Gonad		1.60	0.10	0.17	
P4-Chest		0.90	0.05		
	10				0.101
P4-Gonad		1.30	0.04	0.13	

Table 6. Summary of results of Victoreen 450P dose measurements with the NIH phantom for different NII systems.

Position	MTGR, nSv	MTXR-WE, nSv	TXR, nSv	VACIS-II, nSv	MTXR-LUV, μSv	Rail VACIS, nSv	CXRS, μSv	PFNA (gamma) μSv
P1	40	530	400	50	16	25	21	1.7
P2	42	270	—[a]	—[a]	9	—[a]	22	0.72
P3	33	320	380	47.5	17	20	21	1.38
P4	13	285	—[a]	—[a]	3[b]	—[a]	17.2	1.01

[a] Data not taken due to lack of time. Both systems were in actual operational use.
[b] This low value is probably due to shielding from a dense object.

Table 7. Summary of Landauer radiation dosimetry report of Luxel (OSL) badges used on the NIH phantom for different systems.

Position	MTGR	MTXR-WE	TXR	VACIS-II	MTXR-LUV, μSv	Rail VACIS	CXRS HI/LO, μSv	PFNA[c] (N + G), μSv
P1	M[a]	M	M	M	23	M	113/73	315
P2	M	M	—[b]	—[b]	10	M	67/40	172
P3	M	M	M	M	20	M	115/77	243
P4	M	M	—[b]	—[b]	12	M	43/27	186

[a] All readings indicated by M were below 0.01 mSv.
[b] Data not taken due to lack of time. Both systems were in actual operational use.
[c] Dosimetry measurements taken in the modified FAA configuration have been multiplied by a factor of 1.43 to obtain a value for the proposed field test configuration.

for a single scan, neglecting the shielding from the wall of the truck. It is surprising that the measured values are the same as the calculated value.

Phantom dose equivalents in relation to regulatory limit

It is interesting to compare the radiation dose equivalent received by the phantom during a single scan in each modality to the dose equivalent limit of 1 mSv (100 millirems) in a year, for general public and non-radiation workers, by Federal regulations (NRC 2002). This dose equivalent is in addition to the average background radiation dose of 3.6 mSv (360 millirems) in a year received by individual members of the general public in the United States. Let us assume, for the sake of argument, that an undocumented alien attempts to enter the U.S. a multiple number of times and it so happens that the truck in which he or she is hiding is scanned each time during that year. It is possible to calculate the number of times this person can attempt to enter the U.S. before reaching this limit. This is shown in Table 8.

The chance for anyone trying to make tens of thousands of attempts in vehicles being scanned by gamma-ray imaging systems and thereby reaching 1 mSv (100 millirems) in a year limit is unlikely and very remote. However, the same statement cannot be made for MTXR-LUV, CXR, and PFNA systems.

Phantom dose equivalents in relation to chest x ray

Another way to put the issue of radiation dose equivalent received by an undocumented alien in its proper context is to compare it with the dose equivalent

Table 8. Number of attempts allowed before exceeding the 1 mSv per year dose limit for the general public.

System or modality	Dose equivalent used for calculation	Rounded off number of attempts
RailVACIS	25 nSv (Table 6)	40,000
MTGR	40 nSv (Table 6)	25,000
VACIS-II	50 nSv (Table 6)	20,000
TXR	400 nSv (Table 6)	2,500
MTXR-WE	530 nSv (Table 6)	1,887
MTXR-LUV	2.3 μSv (Table 7)	43
CXRS	115 μSv (Table 7)	9
PFNA	315 μSv (Table 7)	3

received from a medical chest x ray, which is about 0.1 mSv (10 millirems). Hence, the maximum dose equivalent of 50 nSv (5 microrems) from a single scan in the gamma ray imaging systems is at least three orders of magnitude less and does not pose a hazard to the health of the individual exposed.

Phantom dose equivalent in relation to background radiation

Every individual in the United States receives, on the average, a dose equivalent of 3.6 mSv (360 millirems) in a year from background radiation. This background radiation includes natural radiation such as found in the air, water, and ground and also from cosmic rays. It also includes man-made radiation such as chest x rays and medical use of radioisotopes, in addition to exposure from consumer products emitting ionizing radiation. This yearly average of 3.6 mSv (360 millirems) translates to 0.41 μSv (41 microrems) h^{-1}. A person is receiving this radiation whether he or she is aware of it or not. This dose equivalent of 0.41 μSv (41 microrems) received in 1 h is about the same as that received by an undocumented alien in a single pass through the NII systems such as TXR and MTXR-WE. Similarly, for the gamma ray imaging systems, the dose equivalent from a single scan is about the same as, or less than, the background radiation dose equivalent received in 6 min. Since the background radiation dose equivalent is not harmful to individuals, we can say that this additional insignificant amount is also not harmful.

CONCLUSION

Radiation dose equivalents from the sources used in the different modalities were measured with the phantom placed in four positions inside the truck or cargo container. In each case, it does not make a difference if the phantom is standing or reclining. The dose equivalents in the two situations are practically the same. In addition, the measured values are smaller than the values given in the dose modeling report (GSA 2001).

Furthermore, the dose equivalents to the phantom in the gamma ray imaging systems are of the order of tens of nSv (microrems). The dose equivalents in the TXR and MTXR-WE systems are of the order of hundreds of nSv (tens of microrems). The doses in the MTXR-LUV system are of the order of tens of μSv (millirems). Finally, the dose equivalents in the CXRS and PFNA systems are of the order of hundreds of μSv (tens of millirems).

The use of MTXR-LUV system has been discontinued and there is only one CXR system in operation and the PFNA system is not yet ready for deployment pending results of test and evaluation. Hence, all the other NII systems, which constitute the vast majority of systems deployed by BCBP, are relatively safe and under normal circumstances and operating conditions will not cause harm to any stowaways.

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REFERENCES

General Services Administration. Report of analysis of the pulsed fast neutron analysis cargo inspection system. Washington, DC: CH2M HILL, Inc; 2001.

Khan SM. Radiation safety guidelines for a contraband detection system. Washington, DC: USCS Report; 1996.

Nuclear Regulatory Commission. Code of Federal Regulations, 10CFR20 (Standards for Protection against Radiation). Washington, DC: U.S. Government Printing Office; 2002.