Irradiation Decontamination of Postal Mail and High-Risk Luggage

Marc DESROSIERS,[†] Bert COURSEY,[†] Stephen SELTZER,[†] Lawrence HUDSON,[†]
James PUHL,[†] Paul BERGSTROM,[†] Fred BATEMAN,[†] Sarenee COOPER,[†]
Douglas ALDERSON,[†] Gregory KNUDSON,[‡] Thomas ELLIOTT,[‡]
Michael SHOEMAKER,[‡] Joel LOWY,[‡] Stephen MILLER,[‡] John DUNLOP[*]
[†]*Ionizing Radiation Division, Physics Laboratory,*
National Institute of Standards and Technology, Gaithersburg, Maryland, USA
[‡]*Armed Forces Radiobiology Research Institute, Bethesda, Maryland, USA*
[*]*United States Postal Service, Merrifield, Virginia, USA*

Abstract. In October 2001, first class letters, which were laced with *Bacillus anthracis* spores, were sent to political and media targets resulting in five deaths and 22 illnesses, significant mail service disruption, and economic loss. The White House Office of Science and Technology Policy established a technical task force on mail decontamination that included three key agencies: the National Institute of Standards and Technology (NIST); the Armed Forces Radiobiology Research Institute; and, the United States Postal Service. A cooperative effort between this task force and industry led to protocols for the processing of letter and parcel mail.

Currently, NIST is examining the technical issues and barriers to the use of ionizing radiation to mitigate bioterrorism agents in high-risk passenger luggage. The purpose of this work is to develop irradiation specifications, procedures, and protocols that will ensure that broad classes of bioterrorism agents in passenger luggage will be neutralized without damaging luggage contents and inconveniencing passengers with long delays. This work focuses on three areas: the assembly of critical input data, the development of a coupled computational-experimental verification approach for estimating the radiation dose that can be delivered to passenger luggage and the application of the computations to a larger variety of luggage configurations followed by the development of specifications, procedures, and protocols for the irradiation of passenger luggage.

An analysis of the expectations for growth in these and other homeland security areas where irradiation technology can be applied will be discussed.

Introduction

Shortly after the tragic events of September 11, 2001, the terror triggered by the anthrax-causing spore attacks affected every American. Since the postal service is integrated into daily life, the effects were profound. Within the Federal government, these attacks unleashed a flurry of activity aimed simultaneously at the remediation of the exposed facilities and the search for prevention/mitigation methods to halt further attacks. Government agencies were mobilized to address the current emergency as well as for guidance in formulating long-term policy changes. It was soon realized that ionizing radiation was well suited to eradicate the weaponized *Bacillus anthracis* spores dispersed in the nation’s postal system. The Ionizing

Radiation Division (IRD) of the National Institute of Standards and Technology (NIST) was uniquely positioned to bridge the gap between industry and government. As a Department of Commerce agency, NIST's mission to promote and develop measurements, standards and technology enables it to have a close working relationship with their industry stakeholders. In this role, the IRD offered to guide other Federal agencies to the irradiation technology best suited to its needs. The IRD's established trust and credibility with the private sector would also aid in the coordination of the people and facilities required to sanitize the mail in rapid fashion. Accordingly, NIST continues to play a key role in related studies such as the irradiation treatment of high-risk passenger luggage.

1. Mail Sanitation

1.1 Bacillus Anthracis Spore Attacks

NIST quickly ascended to a leadership role in a rapid succession of meetings organized by the President's Office of Science and Technology Policy (OSTP) and the United States Postal Service (USPS). Several NIST staff were assembled to brief a broad range of Federal agencies on industrial radiation-processing technology. NIST's intimate knowledge of the irradiation industry led to invaluable guidance in assessing a safe and cost-effective course of action. Since the IRD operates a national calibration service that routinely certifies industrial irradiation facilities, it was able to attest that they were fully capable of sanitizing the mail with the highest level of quality possible. However, for manufactured products that are commonly sterilized with ionizing radiation, the individual items are identical and their packing within an irradiation container is uniform. Because postal mail is heterogeneous in nature and there was no standard packing pattern or density for the mail, there was a need to demonstrate the efficacy of the process.

As the process had begun in late October 2001, the OSTP formed a task force to develop a plan to validate the irradiation protocol proposed by the Titan Corporation[1] irradiation facility personnel. The technical task force included three key agencies: the National Institute of Standards and Technology; the Armed Forces Radiobiology Research Institute (AFRRI); and, the United States Postal Service. NIST suggested that a series of test-mail letter boxes be prepared. As the technical leaders of the task force, NIST dosimetry experts partnered with spore biologists from AFRRI to design the test. Within 24 h a procedure was agreed upon, and preparations to assemble the test boxes had begun. It was decided to prepare three letter-mail trays in a manner identical to the contaminated mail. This would require that letter mail be packed in "MM" type trays then wrapped/sealed in a biohazard plastic bag. This bagged tray would be inserted into the MM-tray cardboard sleeve and wrapped/sealed a second time in a biohazard plastic bag. The first test-tray box would contain dummy mail with NIST and AFRRI indicators that would be hand carried to the irradiation facility by task-force representatives. A second box was assembled in an identical manner with the exception that this box was marked with an internal label identifying it as containing experimental artifacts; it was shipped through the Brentwood facility with the contaminated mail from there. A third box was prepared and shipped in the same manner as the second; however, this box included a number of non-paper objects in separate articles of

[1] The mention of commercial products throughout this paper does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that products identified are necessarily the best available for this purpose.

dummy mail: coins, CDROM, floppy disk, plastic sheets, metal sheets, and metal paper clips. After the first box was flown to the irradiation facility and processed, the dosimeter materials were removed and measured at NIST while the spore indicators were measured at AFRRI. After the analysis period, and exactly one week from the project's conception, NIST and AFRRI reported to the OSTP and USPS that the tests confirmed that the process was safe. In turn, the OSTP Director endorsed the process and recommended that NIST continue to actively monitor the activity.

The irradiation process is certified by alanine-EPR dosimetry. Alanine dosimeters are of the highest metrological quality and are used by national metrology institutes worldwide to operate their dosimetry services. The uncertainty at the 95% confidence level for alanine pellets is ≈ 2% and for alanine films ≈ 3%. The absorbed doses measured in the Titan-irradiated test boxes were typically double the target minimum dose; some dosimeters measured triple the target minimum dose. Also, for some dosimeters it was obvious that they experienced temperature at or above their melting point (≈ 85 °C). Efforts to modify the protocol to control overdosing are discussed later in this section. Objects (mentioned above) placed into one of the test boxes yielded interesting results. For these tests a radiochromic dosimetry film was used for the measurements; the accuracy and precision of this system is lower (≈ 5% at 95% confidence) than the alanine system, but the radiochromic film offers two-dimensional mapping of the energy deposition. The films were hermetically sealed in a foil pouch (ambient light and relative humidity affect the results) and placed against the objects inside paper envelopes. The objects did not significantly shield the material behind it (Figure 1). This was due to the fact that the boxes are flipped 180° midway through the treatment. The floppy disk was not readable because of damage to the plastic case; however, although the CDROM jewel case was severely damaged, the CDROM was readable. Figure 2 shows the dose distribution within the plane of an envelope irradiated end-on (electron beam parallel to the long side of the envelope plane).

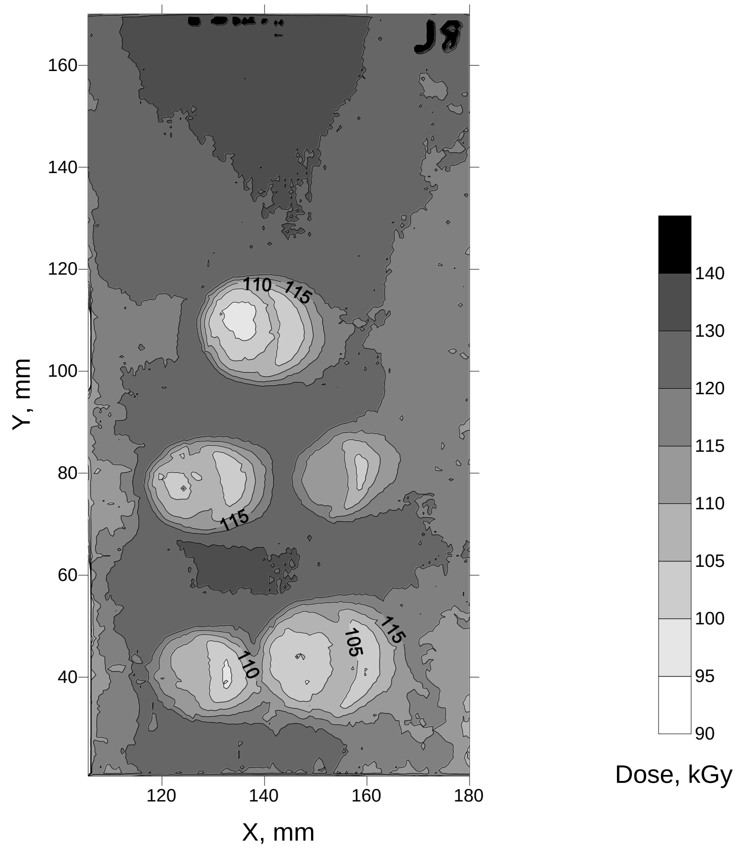

Figure 1. Radiochromic-film dose map mounted against coins in an envelope. The dark marks at the top of the image are for identification.

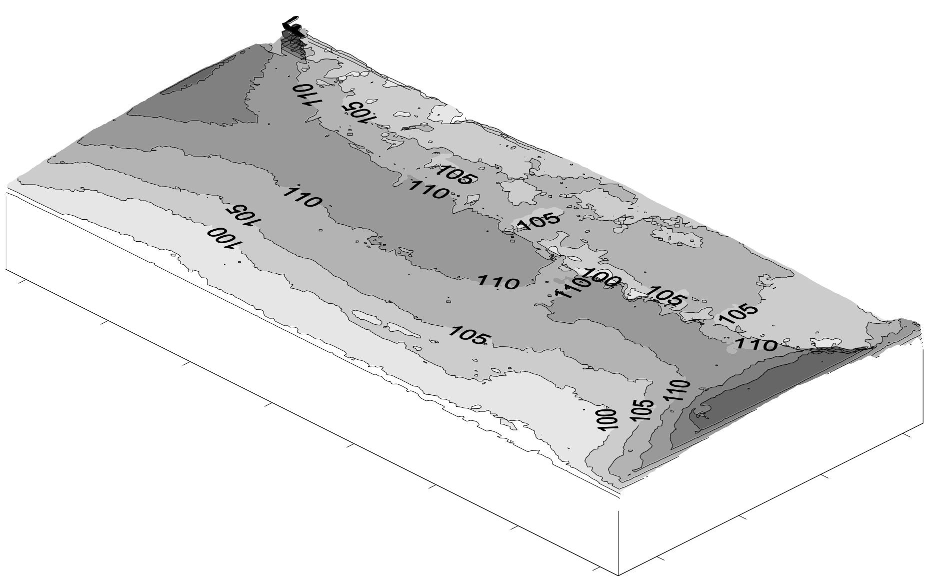

Figure 2. Radiochromic-film map of dose distribution within the plane of an envelope (doses in kGy). The dark mark in the upper corner of the image is for identification.

Shortly after the mail sanitation work began, it was realized that the throughput of the Titan facility coupled with the large volumes of contaminated mail at the Brentwood and Trenton mail facilities would cause unacceptable delays in the mail-delivery times. Moreover, in addition to letter mail, so-called "flats" or large envelopes and magazines, along with packages of larger dimensions, had to be processed. The electron-beam accelerator characteristics for this particular Titan facility would not be appropriate for the processing of large packages. Thus, a second facility, Ion Beam Applications (IBA), was contracted to irradiate mail. For the Titan facility letter mail was stacked vertically into trays and the trays were stood on end and moved through the horizontal electron beam. The IBA facility used a vertical electron beam, and the mail was stacked flat in the tray to avoid any issues with the shifting of contents when the mail trays were flipped for a required second pass through the beam. Because the IBA facility design was different than that for Titan facility, this process was once again validated. The alanine dosimeters in these test boxes measured doses predominately 50 % to 100 % greater than the target minimum dose. These data are much more typical of the dose range experienced in industrial processing. The absorbed dose measured in the center of a stack of flats was about 50 % greater than the target minimum dose.

Operating in an emergency mode from the onset, mail irradiation did not enjoy the normal period of planning, design and testing that would optimize the process from the perspectives of the irradiation process and product quality. To facilitate this, NIST acted as an intermediary between the processors and the packers. To achieve product consistency, NIST worked with the USPS to gather feedback on the product quality to formulate packing guidelines, and then coordinated this with industrial irradiation facilities by setting acceptance criteria for letter trays. Some of the early inconsistencies in packing coupled with conservative irradiation settings led to an over-irradiated product. The chemical degradation from the combined effects of radiation, heat, steam and ozone, produced undesirable physical effects in the mail quality and allergic reactions for some of the more sensitive mail recipients. Early improvements in mail quality were achieved through NIST-improved packing guidelines. NIST also revised irradiation settings through an additional series of on-site tests using the NIST alanine dosimetry system. However, since the mail from the Brentwood and Trenton mail facilities were double-bagged because of their contamination level, the recommendation to slit these bags open for venting immediately after irradiation had one of the most profound effects on the mail quality. Large packages were the last to be sanitized. For this application, highly penetrating bremsstrahlung (high-energy x-ray) beams are required to treat the wide range of package dimensions expected. Totes were constructed (102 cm long, 61 cm wide, 91 cm high) to contain the packages and tests were conducted with surrogate packages. This process is slower and requires more passes through the beam; however, the resulting dose distribution is far more uniform and the mail quality is much improved.

This cooperative effort between NIST, Ion Beam Applications (IBA) and the USPS led to protocols for the processing of parcels with high-energy x rays (from electron beam conversion). About this same time, a team of Federal government and industry representatives drafted a documentary standard that set requirements for validation and routine control of the decontamination process.

In the first year, ≈ 3 million articles of contaminated mail were sanitized and safely delivered to their destination (the total for all mail irradiated in the first year is ≈ 70 million). Some Federal government mail (defined by zip code) continues to be treated with ionizing radiation. At the end of 2003, about 4000 tons of letter mail and 200 tons of parcels had been sanitized since the process began late in 2001.

2. Radiation Treatment of Passenger Luggage

2.1 Threats to Agriculture

The agricultural industry continues to guard against foreign pests that threaten severe economic consequences. The U.S. Animal and Plant Health Inspection Service (APHIS) defends against this threat every day at more than 80 international airports throughout the United States. Approximately 100 million passengers carry 150 million articles of luggage through these ports each year. About 30 % of this luggage is categorized as high risk. Inspecting upwards of 50 million articles of luggage is a formidable task. The new threats posed by terrorism have raised the level of concern for APHIS inspectors. As increasing the number of inspectors is difficult due to budget constraints, APHIS is considering a technological solution to mitigate these threats.

2.2 Feasibility Study

NIST has a study in progress to examine the technical issues and barriers to the use of irradiation to mitigate common bioterrorism agents and insects in high-risk passenger luggage. The attractive features of this solution are: the individual pieces of luggage do not have to be physically opened and inspected; bioterrorism agents that are concealed, or not easily identified by an inspector, can be treated; the risk of contaminating inspectors or facilities using this treatment method is very low; and, radiation doses can be selected to neutralize a variety of bioterrorism agents, diseases and insects.

Most concerns regarding the radiation sensitivity of luggage contents are not at issue because a large number of common items (*e.g.*, food) are prohibited. However, care should be taken to minimize the absorbed dose to luggage and its contents as not to destroy or render them unusable. Another consideration is throughput; the irradiation equipment must be capable of processing luggage at a rate that does not significantly delay passengers. The purpose of this study is to develop irradiation specifications, procedures, and protocols that will ensure that broad classes of bioterrorism agents in passenger luggage will be neutralized without damaging luggage contents and inconveniencing passengers with long delays. To date, the work has focused on the assembly of critical input data and the development of a coupled computational-experimental verification approach for estimating the radiation dose that can be delivered to passenger luggage.

2.3 Bioagent Data

The list of agents considered a threat to U.S. agriculture and commerce was assembled and a list of their D_{10} values is presented in Table 1. The D_{10} value is the radiation dose required to reduce the population of bacterial pathogens by 90 %.

Table 1. The published D_{10} values for selected microorganisms.

Organism	D_{10} Value (kGy)	Substrate	Temp. (ºC)	Ref.
Campylobacter jejuni	0.16 - 0.20	Poultry	5	[1]
Escherichia coli O157:H7	0.30	Beef/Poultry	5	[2,3]
Listeria monocytogenes	0.45	Beef	5	[3]
Salmonella spp.	0.70	Beef	5	[3]
Staphylococcus aureus	0.46	Beef	5	[3]
Bacillus cereus spore	2.46	Beef	5	[4]
Clostridium botulinum	3.56	Poultry	-30	[5]
Moraxella nonliquifaciens	5.3 - 5.8	Beef	-30	[6]
Bacillus anthracis	5.5		ambient	[7]
Foot & mouth disease	5.3		-68	[8]
Swine vesicular disease	1.1 - 5.2		ambient	[9]
Vesicular stomatitis	2.9		-68	[8]
Newcastle	5.2		ambient	[9]
Rift Valley fever	< 2.0		ambient	[10]
Bluetongue	8.3		-68	[8]
Sheep/goat pox	2.2		ambient	[10]
Hog Cholera	5.5		ambient	[8]
Influenza A	2.5 - 7.1		-40	[9,11]

2.4 Luggage Data

Typical airline luggage restrictions for ordinary handling are a total linear length (length + height + width) ≤ 1.57 m (62 in.) and a total weight ≤ 31.8 kg (70 lbs). However, virtually any size and weight can be transported on board. Luggage dimensions were collected from sales information of well-known luggage merchandisers. Information on a total of 138 models/sizes of luggage was collected, including type, construction, and dimensions. The collection ranges from small beauty cases, through roll-on cases, garment bags, duffels, wardrobes, up to foot lockers and steamer trunks. This information serves as a guide to available luggage, their dimensions, and their compositions. The luggage volumes ranged from 0.02 m^3 to 0.28 m^3. These sizes require the use of the more penetrating bremsstrahlung (high-energy x-ray) beams. The size of a carrier (tote) used to transport the luggage through the radiation beam was compatible with the steel tote used by IBA in their irradiation of U.S. Postal Service parcels.

A representative set of unclaimed airline luggage (with contents) was lent to NIST by the Federal Aviation Administration (FAA) for this study. The sizes cover the typical range, with the possible exception of the extra-large trunks, and are representative in weight and construction material extracted from the FAA database. The densities range from 0.11 g/cm^3 to 0.33 g/cm^3, with a mean of 0.16 g/cm^3. A container filled with only close-packed books could have a density up to ≈ 0.75 g/cm^3, and we plan to assume this value for the highest density expected for benign contents of luggage in future calculations.

2.5 Test Runs at 5 kGy

Four test totes were irradiated at the IBA facility, using their 5 MeV x-ray beam for a target test dose of 5 kGy. The test included ≈ 200 dosimeters along with temperature sensors placed in the tote/luggage filler material. The beam-processing parameters were 5 MeV beam energy and 25 mA beam current; four passes were used to achieve a 5 kGy dose. All temperature sensors failed to register the minimum value on the detector (37 °C); data diskettes and CDROMs included in the luggage were readable after irradiation; and there was no obvious damage to luggage or contents. The dosimeters all measured between 4.8 kGy and 6.9 kGy, indicating that reasonably small variations in absorbed dose can be expected for typical luggage irradiated by such a beam.

The intent of the tote 1 was to test the ability to model a pure homogeneous container using a homogeneous product with a density and composition close to that of average passenger luggage. The tote was completely filled with large sheets of corrugated cardboard such that the x-ray beam is normal to the large face. Alanine-film dosimeters were placed along three perpendicular axes with the origin at the center of the tote. Dosimeters were placed at 5 cm intervals along the centerline in the beam direction (z axis). On the plane perpendicular to the beam axis in the middle of the tote, dosimeters were placed at 10 cm intervals from the z axis to the cardboard-pad edges to confirm beam and dose uniformity. Additional dosimeters were placed on the front and back cardboard pads near their corners to probe possible dose depression due to edge effects. In the horizontal conveyor (belt) direction, the dose distribution is relatively flat and symmetric, with some increase at the edges presumably due to in-scatter from the steel tote walls. Along the vertical scan dimension, the fairly symmetric dose distribution peaks in the center and droops at the top and bottom presumably due essentially to out-scatter of the photons. The doses in the corners of the central plane are in agreement with the top and bottom doses.

Tote 2 was completely filled with luggage; the contents of each bag included corrugated cardboard, copy paper, or plastic clips. The bags were constructed from a variety of materials, and dosimeters were located in the center of each bag.

Table 2. Dosimetry results for tote 2.

Luggage Description	Contents	Density of Contents (g/cm^3)	Dimension Along Beam (cm)	Absorbed Dose (kGy)
hard shell	copy paper	0.75	21.0	4.7 - 5.0
hard plastic	cardboard	0.19	44.5	5.8 - 6.0
particle-board footlocker	cardboard	0.16	36.5	5.6 - 5.7
soft polyester	plastic clips	0.26	48.3	4.8 - 4.9

Tote 3 was a real-world scenario of bags containing a variety of materials and personal contents. This tested the feasibility of sanitizing in the mode where there are multiple bags deep along the beam direction by measuring the uniformity of dose from bag to bag. Each bag was completely filled with a variety of clothing and other common personal contents that included diskettes, film in a lead pouch, *etc*. Each bag included centrally located dosimeters. Also, the possible radiation-shielding effects of high-Z materials was tested by including an assembly of two 3 mm thick steel plates, placed perpendicular to the beam direction, sandwiching a plastic plate into which a vial of alanine-pellet dosimeters was inserted.

Table 3. Dosimetry results for tote 3.

Description	Average Density (g/cm^3)	Absorbed Dose (kGy)
soft vinyl	0.10	6.1 - 6.3
soft polyester and vinyl carry on	0.11	5.5 - 5.9
soft polyester day pack	0.09	5.6 - 5.8
hard plastic	0.18	5.3 - 5.9
soft vinyl	0.11	5.8 - 5.9
cloth (no frame)	0.15	5.2 - 5.8
leather	0.19	5.2 - 5.9
soft vinyl carry on	0.22	5.6 - 5.9

The absorbed dose inside the lead-pouch film bag was 5.5 kGy; the doses measured on either side of the bag exterior were 5.5 kGy and 5.7 kGy. The absorbed dose between the steel plates was 5.2 kGy; the doses measured on either exterior side of the steel plates were 5.0 kGy and 5.6 kGy.

The purpose of tote 4 was to measure the dose obtained in a single-bag irradiation configuration with its short dimension along the beam direction, as a possible real-world scenario in which each bag is placed individually on a moving conveyor. The measured doses ranged from 6.4 kGy to 6.9 kGy.

2.6 Test Runs at 25 kGy

Test irradiations were done on five totes at IBA with a target minimum dose of 25 kGy. The beam-processing parameters conditions were 5 MeV beam energy and 25 mA beam current. Tote 1 served as a reference and was filled with a homogeneous product; as in the 5 kGy runs, it was completely filled with large sheets of corrugated cardboard such that the x-ray beam is normal to the large face. The dosimetry confirmed that the depth-dose patterns were comparable to the 5 kGy test.

Tote 2 included three pieces of newly purchased luggage to assess radiation damage at 25 kGy. The balance of the tote was filled with used luggage. Various experiments were included in separate bags. One bag included a "steel sandwich" experiment identical to that of tote 3 in the 5 kGy run described in the preceding section, except that the steel thickness was increased to 1.27 cm; the remainder of the bag was filled with bubble wrap. The dosimetry and computer modeling for this test is shown in Figure 3.

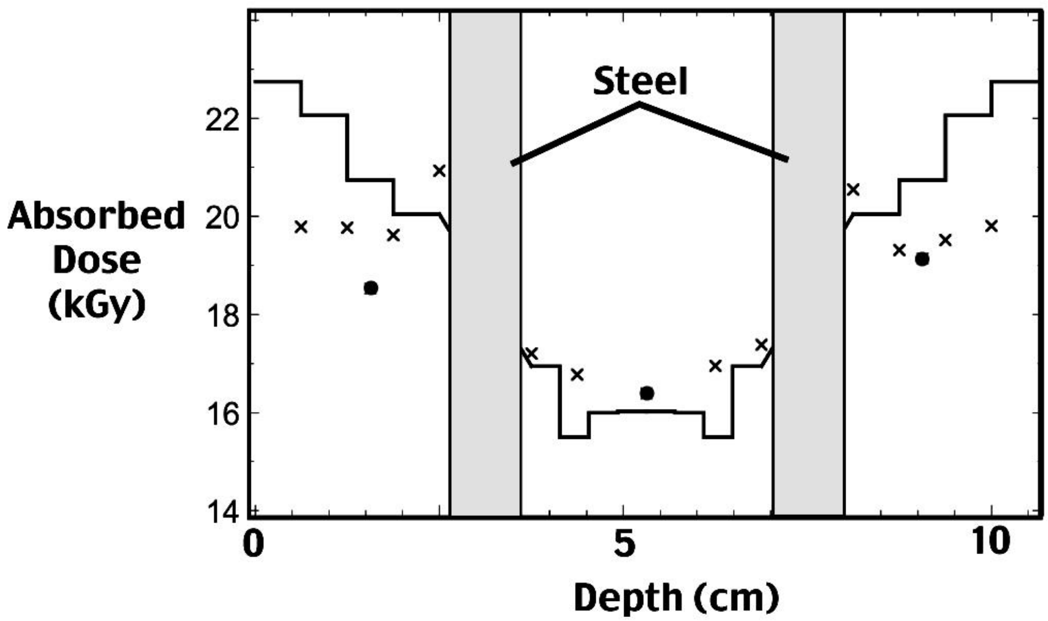

Figure 3. Depth-dose distribution through steel plates: Monte Carlo calculation (–); alanine film dosimetry (x); and alanine pellet dosimetry (•).

Tote 3 was used to determine the dose delivered inside a lead-shielded container. A lead box with 1 cm thickness was placed inside a trunk filled with cardboard. The lead box contained cardboard and alanine dosimeters. Dosimeters were also placed outside the lead box along the beam direction. The dosimetry results are shown in Figure 4.

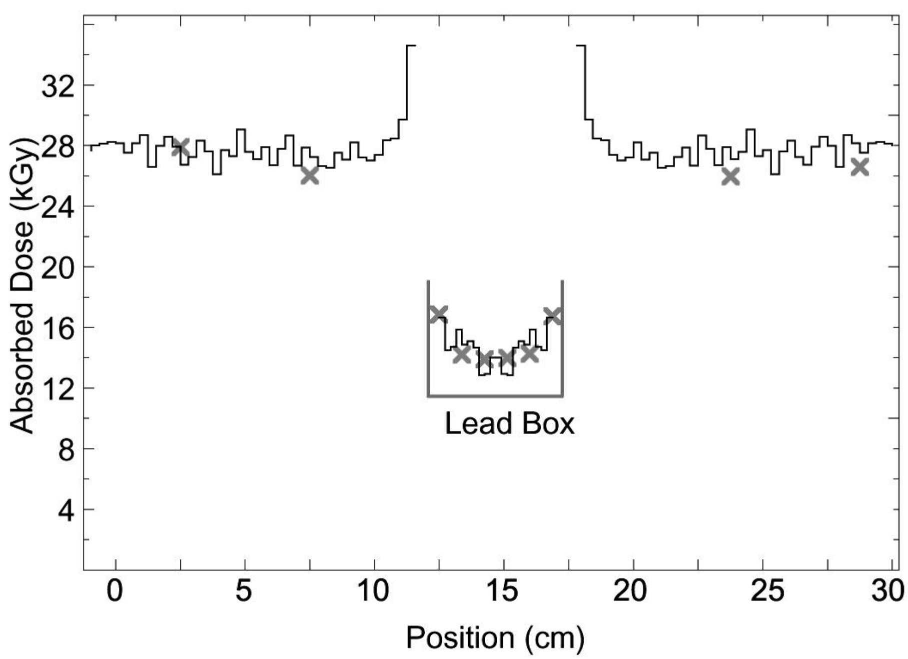

Figure 4. Depth-dose distribution through a lead box: Monte Carlo calculation (–); alanine dosimetry (x).

Tote 4 was designed to measure the dose distribution in a high-density product, namely, copy paper at 0.75 g/cm^3. Dosimeters were placed between packages of paper, each containing 500 sheets, to measure the distribution of absorbed dose along the beam direction. These data are shown in Figure 5.

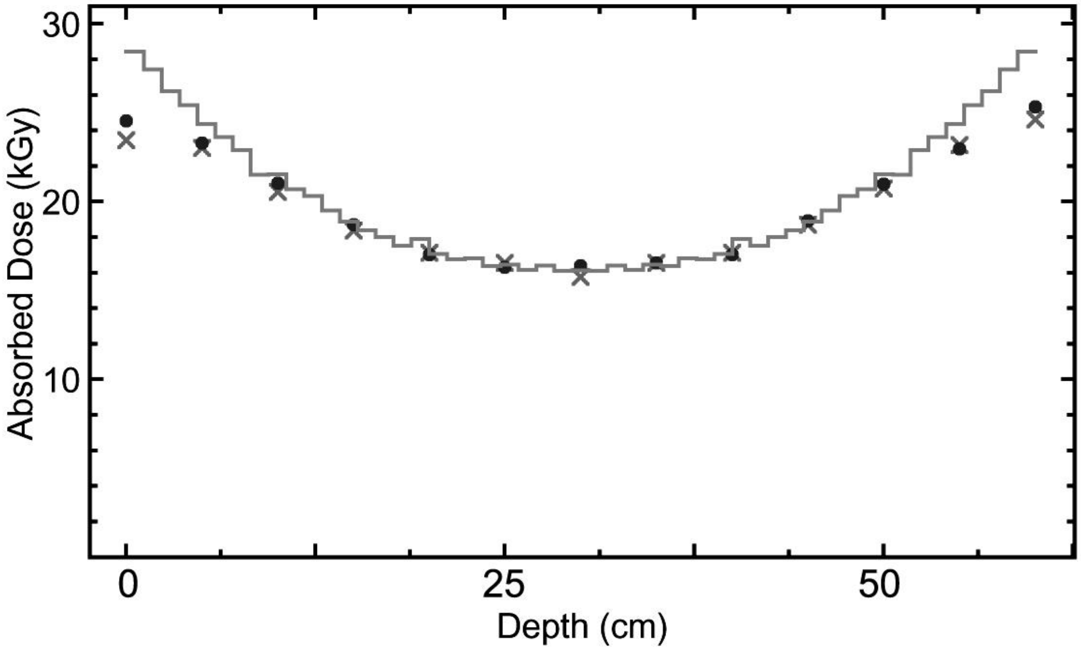

Figure 5. Depth-dose distribution through totes filled with paper: Monte Carlo calculation (–); alanine dosimetry in the middle tote (x) and end tote (•).

The measured maximum temperatures for the different totes ranged from 40.0 ºC to 48.9 ºC. Other observations included: no noticeable structural damage to luggage (new or used); odors from radiolytic products and ozone were similar to that of irradiated mail; yellowing of plastic in blister pack containing batteries (batteries remained functional); CDROMs and diskettes were undamaged and readable.

2.7 Monte Carlo Simulations

The specifics of the IBA TT300 Rhodotron (proprietary information) were obtained from IBA to aid the Monte Carlo calculations. The three-dimensional Monte Carlo calculations have been developed by altering MCNP4C code to obtain photon phase-space data of the bremsstrahlung output. These phase-space data are used as the source term for calculations of the subsequent transport through the uniform-cardboard tote assembly (and later through any complex configuration) by an altered version of the ACCEPT/ITS3 code. The three-dimensional Monte Carlo results were obtained in two steps. In the first step, calculations were done for a simplified model of the bremsstrahlung source using the Monte Carlo code MCNP. MCNP is a three-dimensional Monte Carlo transport code for electrons, photons and neutrons, the first two particle types being relevant to this work. The necessary output of this run was a description of the phase space of the particles exiting the bremsstrahlung converter. The phase-space results were obtained for the static case of a beam of 5 MeV (and, later, 7

MeV) electrons of a fixed spot size incident normally on the converter. The bremsstrahlung output generated using MCNP was later checked against a simulation using the PENELOPE code. Minor differences were observed at low photon energies. The second part of the calculation is the actual modeling of the transport of the bremsstrahlung photons through the totes. The desired output was the dose to the product contained within the totes. The calculation is naturally split in this way, as the generation of the phase space is quite time consuming relative to the dose calculation, and the same phase-space description can be used regardless of what fills the totes. In this second step, the MCNP code could have been utilized. However, due to some well-known inadequacies of this version of the code in the treatment of problems with many transport zones, the ACCEPT code from the Integrated Tiger Series (ITS) was used in this second part. A code was written to process the MCNP output into a form that could be utilized by ACCEPT. The ACCEPT code was modified to admit a phase-space source and to scan that source along the directions of the scan horn as actually occurs in the Rhodotron. The motion of the totes along the conveyor was simulated by scanning the source along the direction of the conveyor, enabling a realistic simulation of this dynamic system. Wide-angle bremsstrahlung emission from the source was discarded in accord with the physical collimation utilized by IBA. The actual product configuration was faithfully modeled as six totes, stacked two-high along the direction of the scan horn and three-wide along the direction of the conveyor belt. The dose was obtained *versus* depth into the cardboard for the center two totes, the outer four totes serving to realistically model the attenuation and scatter of the photons emitted at large angles. Often times, in modeling a system, some details of the configuration are obscure or missing. This usually makes it necessary to normalize to experiment in one case. In our investigations, enough detail was available to avoid this normalization step.

Still, the Monte Carlo simulations can not be expected to exactly match the measured doses, due variously to imperfect knowledge of the actual details and performance of the accelerator system and of the tote and contents, as well as to uncertainty in the measured results. Figure 5 is a comparison of the experimental data with the Monte Carlo calculations for a tote, where the distribution of absorbed dose is in the direction of the beam. Clearly, the calculated and experimental results show some differences; the calculated results show a rise at the interface with the tote walls with respect to the center of the totes whereas the experimental data are more uniform. However, these results demonstrate that the simulations can serve as a reasonable guide and can confidently be used as a predictive tool in the absence of measurements.

3. Other Opportunities

3.1 Imports

Ship containers entering the country through several major U.S. ports pose a significant smuggling risk. A means to x-ray these containers to examine their contents that would not significantly reduce the throughput would aid security efforts. Because U.S. inspection agencies can set container guidelines to suit the inspection technology; all options are open to facilitate this type of inspection service.

3.2 Military and Law-Enforcement Applications

U.S. military troops face the threat of chemical- and biological-agent attacks throughout the world. There is a possibility that military materials might need to be decontaminated. Here, field-deployed portable electron-beam accelerators are a reasonable solution. Along these same lines, the decontamination of physical evidence should be considered; this application would apply to national and international law-enforcement agencies as well. The use of ionizing radiation to decontaminate materials questions the applicability of standard forensic tests used in law enforcement. As a first test, the Ionizing Radiation Division and Biotechnology Division of NIST collaborated to show that a high dose of ionizing radiation does not interfere with standard DNA profiling tests [12].

3.3 Basic Research

Volatile organic irritants and the degradation of paper resulting from the mail irradiation process underscore the need for radiation-effects studies on common materials for safety and archival efforts. The radiation effects on certain sensitive materials such as magnetic media and their packaging material should also be examined.

Another issue is the consideration to improve irradiator throughput by raising the photon energy from 5 MeV to 7 MeV; a risk assessment for induced activity is needed.

3.4 Critical Data

The research described in this paper relies heavily on the quality of published D_{10} values. A reevaluation of these data by a team of recognized experts would be welcomed by the research community. A committee of plant- and animal-pathogen experts should be convened and tasked with assembling and evaluating the available data with the intent of producing a report that summarizes their consensus opinion.

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