NIST Ionizing Radiation Division Report to the CCRI(I) 2009-2010

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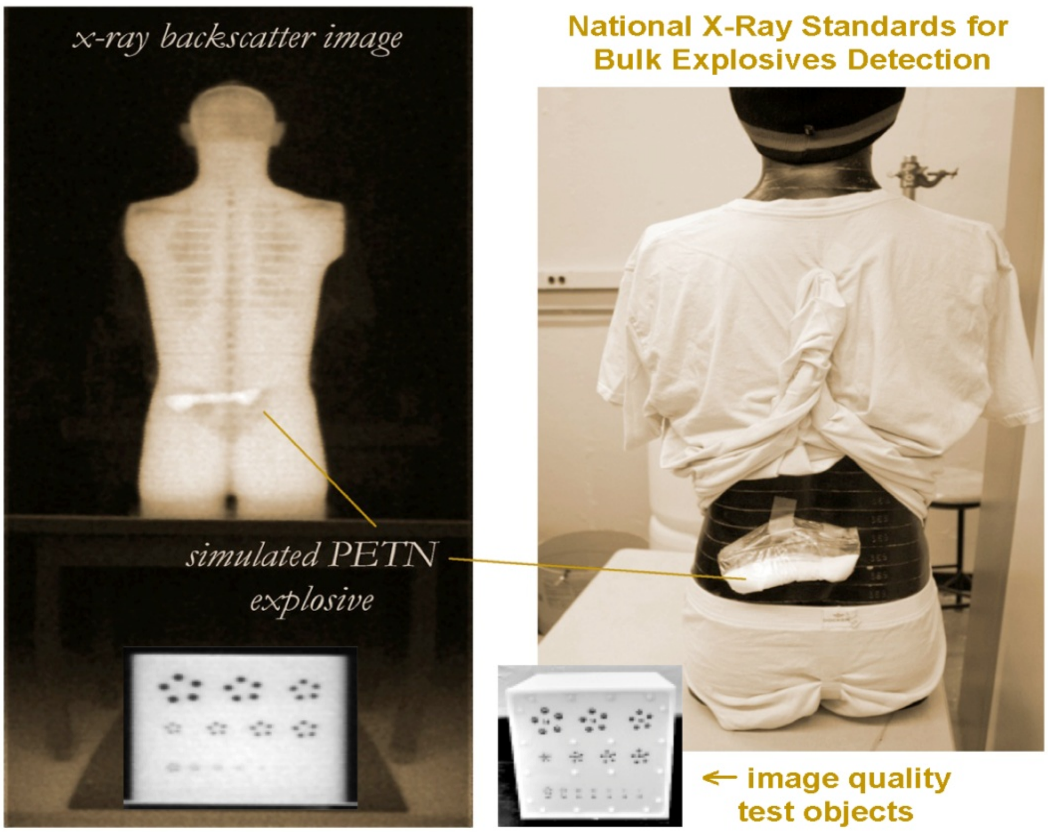

National x-ray standards for bulk explosives detection have been developed and used in the evaluation of instrumentation already, or planned to be, deployed in US airports. X-ray backscatter image of anthropomorphic phantom and ANSI N42.47 test object (left) and photographs of the same (right). The contents of a bag of simulated pentaerythritol tetranitrate (PETN) explosive are clearly visible in the x-ray scan.

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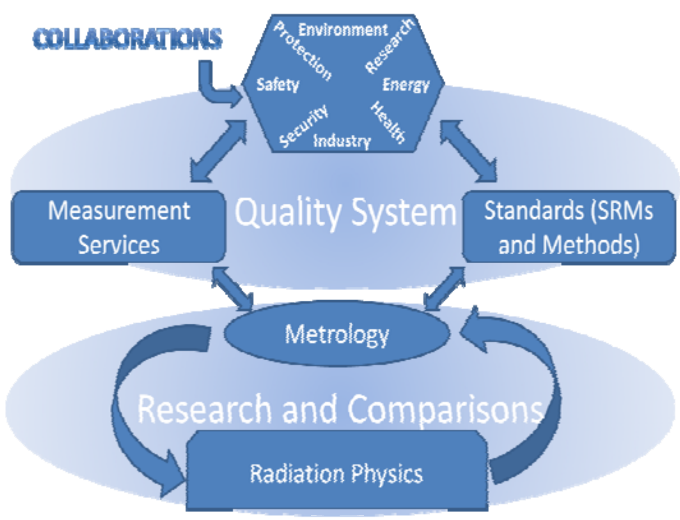
Ionizing Radiation Division

INTRODUCTION

The mission of the Ionizing Radiation Division is to provide the foundation of ionizing radiation measurements for the Nation. The strategy for meeting this goal is to develop, maintain, and disseminate the national standards for ionizing radiation and radioactivity to meet national needs for health care, U.S. industry, and homeland security. This strategy consists of three elements:

- Develop and provide measurement standards in the dosimetry of x rays, gamma rays, and electrons, and engage in research on radiation interactions and effects.
- Develop and provide standards and measurements for neutron dosimetry and neutron sources, and maintain and support fundamental neutron physics user facilities and advance research in fundamental neutron physics.
- Develop and provide measurement standards for radioactivity, and develop and apply radioactivity measurement techniques and engage in related research.

Building from programs ranging from fundamental research in radiation and neutron physics to supporting research in metrology (informed by applied research focused on specific industry sectors), the Division provides critical measurements and standards for all aspects of ionizing radiation in industry, health care, the environment, homeland security, worker protection, energy, defense, and scientific research. Working closely with the user communities in all of these fields enables us to define and prioritize our research and programs in metrology, while an active quality system provides the support needed for confidence in final measurements and high-quality customer service.



The Division, part of NIST's Physical Measurement Laboratory (PML), fulfills its mission through activities in three technical groups: Radiation Interactions and Dosimetry (led by Michael G. Mitch), Neutron Interactions and Dosimetry (led by Muhammad Arif), and Radioactivity (led by Michael P. Unterweger). In addition to promoting the accurate and meaningful measurements of dosimetric quantities pertaining to ionizing radiation (x and gamma rays, electrons, and energetic, positively charged particles), the Division maintains the national measurement standards for the Système International (SI) derived units for radiation dosimetry (the *gray*) and activity (the *becquerel*). It also provides measurement services, standards, and fundamental research in support of NIST's mission as it relates to neutron technology and neutron physics for industrial research and development, national defense, homeland security, electric and alternative power production, and radiation protection, and maintains and disseminates measurement standards for neutron dosimeters, neutron survey instruments, and neutron sources. Finally, the Division is responsible for developing metrological techniques to standardize new radionuclides for research, and for exploring radiation and nuclear applications in health care, worker protection, environmental protection, and national defense.

Radiation Interactions and Dosimetry: The Radiation Interactions and Dosimetry Group advances the measurement of quantities important in the radiological sciences through programs in the dosimetry of x rays, gamma rays, electrons, and other charged particles. Its mission is to develop, maintain, and disseminate the national measurement standards for these radiations, and to engage in research on radiation interactions and effects to meet requirements for new standards and to address the needs of industry, medicine, and government. These standards are disseminated both directly to the customer and through networks of secondary calibration laboratories by means of calibrations and proficiency testing services provided to maintain measurement-quality assurance and traceability. We maintain the national standards for the *gray*, the Système International (SI) unit for radiation dosimetry, and develop, maintain, and disseminate high-quality data on fundamental radiation interactions.

The Group maintains several electron accelerators, including the Medical Industrial Radiation Facility (MIRF, based on a 32 MeV traveling wave electron linac), and the Medical Electron Accelerator Dosimetry facility (MEAD, built around a Varian Clinac 2100C). The MEAD facility was recently employed in a bilateral comparison between NIST and the Bureau International des Poids et Mesures (BIPM) of absorbed dose to water standards for high-energy accelerator photon beams. Radiation interaction data are used extensively in radiation transport calculations and simulations, employing algorithms and codes often developed by our staff, to solve a wide range of problems in radiation science. A computational model of the Clinac 2100C accelerator was developed, and wall corrections were calculated for a cavity ionization chamber that will allow direct realization of air kerma from megavoltage x-ray beams typically used in cargo inspection systems.

A vacuum double-crystal spectrometer (VDCS) is being used to generate absolute x-ray reference wavelengths from 1.2 nm to 0.1 nm (1 keV to 12 keV), traceable to the definition of the meter, at the femtometer level of accuracy and precision. X-ray wavelength measurements are performed in support of high-accuracy transfer standards needed in fundamental experiments at NIST and around the world.

In 2010, NIST calibrated its 1,000th low energy, low-dose-rate brachytherapy seed using the Wide-Angle Free-Air Chamber (WAFAC). A new laboratory dedicated to establishing a national primary air-kerma rate standard for miniature x-ray sources (< 50 keV) used in brachytherapy was developed. Research in water calorimetry aims to develop primary absorbed dose to water standards that address metrological challenges posed by the dynamic, nonstandard radiation fields with narrow beam cross sections and high dose gradients used in modern 3D conformal radiation therapy. The Group is also pursuing small-field therapy dosimetry studies using alanine pellets and electron paramagnetic resonance (EPR) spectrometry.

With support from the Department of Homeland Security (DHS), the Group facilitates the development of and maintains technical-performance standards for various types of x-ray security-screening systems that are used to detect bulk explosives and other illicit items. NIST provides support to the Domestic Nuclear Detection Office (DNDO) of the DHS for their advanced non-intrusive inspection (NII) initiatives, including radiation dosimetry in and around cargo screening systems and evaluation of the image quality of these systems.

The first comparison of air-kerma standards for mammography x-rays between NIST and the BIPM was recently completed. A bilateral comparison of air-kerma standards from ^{137}Cs and ^{60}Co beams was conducted between NIST and the International Atomic Energy Agency (IAEA) to support international efforts for harmonizing radiation protection measurements around the world, ensuring the safety of radiation workers and the public.

Neutron Standards and Measurements (for update on Technical Activities, please refer to report to CCRI Section III): The Neutron Interactions and Dosimetry (NI&D) group, located at the NIST Center for Neutron Research (NCNR), maintains and supports the nation's premier fundamental neutron physics user facilities, including a weak interactions neutron physics station, Neutron Interferometry and Optics Facility (NIOF), Ultra Cold Neutron Facility (UCNF) and a ^{3}He based Neutron Polarizer development facility, and has developed the nation's only high-resolution neutron imaging user facility (NIF) for fuel cell research. We maintain, and disseminate measurement standards for neutron dosimeters, neutron survey instruments, neutron sources, and improve neutron cross-section standards through both evaluation and experimental work.

The group is at the forefront of basic research with neutrons. Experiments involve precision measurements of symmetries and parameters of the "weak" nuclear interaction, including measurement of the lifetime of neutrons using thermal and ultra-cold neutrons, improved cold neutron counting techniques, setting a limit on the time-reversal asymmetry coefficient, and radiative decay of the neutron. The neutron interferometry program provides the world's most accurate measurements of neutron coherent scattering lengths important to materials science research and modeling of the nuclear potentials; during 2009-2010, new interferometry experiments to determine the charge distribution of the neutron, and reciprocal space imaging were carried out. We are developing and promoting the applications of efficient neutron spin filters based on laser-polarized ^{3}He. We are pursuing applications for these filters at the NCNR, the Intense Pulsed Neutron Source at Argonne National Laboratory, and the Los Alamos Neutron Science Center.

We are developing the necessary technical infrastructure to support neutron standards for national security needs. In addition, we are developing advanced liquid scintillation neutron spectrometry techniques for characterization of neutron fields and for detection of concealed neutron sources with low false-positive rates. We are participating in a Consultative Committee for Ionizing Radiation (CCRI) comparison of thermal neutron fluence rate measurements, characterizing four different beam qualities at the NCNR, and carrying out comparisons of NIST standard neutron sources. We are also leading an effort that will result in a new international evaluation of neutron cross-section standards.

We are applying neutron-imaging methods for industrial research on water transport in fuel cells and on hydrogen distribution in hydrogen storage devices. This facility has provided critical services to major automotive and fuel cell companies during 2009-2010. This is a high demand and high profile nationally recognized program.

In summary, the NI&D group provides measurement services, standards, and fundamental research in support of NIST's mission as it relates to neutron technology and neutron physics. The national interests served include industrial research and development, national defense, homeland security, higher education, electric power production, and, more specifically, neutron imaging, scientific instrument calibration and development, neutron source calibration, detection of concealed nuclear materials, radiation protection, and nuclear and particle physics data.

Radioactivity (for update on Technical Activities, please refer to report to CCRI Section II): The Radioactivity Group develops and improves the metrological techniques used for the standardization of radionuclides, and carries out a wide range of programs in low-level standards for environmental measurements and monitoring, standards for nuclear medicine, standards and testing criteria for radiological instrumentation used for security, and radionuclide metrology. Its mission is to develop, maintain, and disseminate radioactivity standards, develop and apply radioactivity measurement techniques, and engage in research to meet the requirements for new standards. Our participation in international comparison exercises has kept us abreast of efforts of other laboratories and helped us to maintain our own capabilities.

We continue to lead the national effort, in collaboration with the Department of Homeland Security, to develop standards and protocols for radiation instrumentation for early and emergency responders. We have developed an accreditation program with National Voluntary Laboratory Accreditation Program (NVLAP) for instrument testing. We are also continuing to spearhead the development of American National Standards Institute (ANSI) standards and testing protocols for spectroscopic portal monitors, neutron detectors, x-ray and high energy gamma-ray interrogation methods, x-ray imaging, data formats for instrumentation data output, and training standards for responders. Significant work has been done on developing tests including radiation detection instruments to be deployed in airports and boat-mounted for maritime applications.

The Group continues to lead an internationally-recognized program for standards in nuclear medicine, providing the national standards for radionuclides used in 13 million diagnostic procedures and 200,000 therapeutic nuclear medicine procedures annually in the US. Secondary standards for the alpha-emitter ^{223}Ra were developed in the form of empirically derived calibration settings for the most commonly used dose calibrators, thereby allowing accurate measurements of this radionuclide to be made in the clinic. This is expected to lead to improved dose estimates to be made of radiopharmaceuticals that incorporate ^{223}Ra, which will lead to increased safety and effectiveness.

During the past two years, a large effort has been focused on the development of standards and measurement methodologies to improve the quantitative capabilities of Positron Emission Tomography-X-ray Computed Tomography (PET-CT) and Single-Photon Emission Computed Tomography (SPECT) imaging. As part of the America Recovery and Reinvestment Act (ARRA), the group was awarded $2.4M to acquire a clinical PET-CT scanner to act as the centerpiece of a new facility being established to support the medical imaging standards program. Renovation of the laboratories and installation of the scanner is expected to be completed by the end of 2010.

The Group's environmental program leads the community in low-level and natural matrix material measurements and standardization, and continues to be heavily involved in the world-wide measurement of environmental-level radionuclide dispersal and contamination through a large number of international intercomparisons and traceability programs and Standard Reference Materials (SRM®s). An extensive program for nuclear forensics methods development, validation and performance evaluation has been established.

Revitalization of our basic metrology capabilities has involved extensive work in many areas. The construction of a second-generation Triple-to-Double Coincidence Ratio (TDCR) system has been constructed and is now in use. The principle method of primary standardization at NIST is live-timed $4\pi\beta$-γ anticoincidence counting. During the past two years, NIST researchers have adapted this method to perform primary measurements on a variety of radionuclides. The Group has participated in a number of international intercomparisons as well as the submittal of samples to the System International Reference (SIR). A new automated ionization chamber has been developed at NIST to measure up to 100 samples with programmable sample queuing, sample handling and measurement parameters.

Interactions with user groups (including the Council on Ionizing Radiation Measurements and Standards, or CIRMS), collaborations with colleagues from other laboratories around the country and world-wide, and input from independent reviews (e.g., National Research Council Panel technical reviews, the NIST Visiting Committee on Advanced Technology, quality system assessments, etc.) are used to identify the most relevant and immediate needs for measurement services to support the breadth of applications where ionizing radiation is used or controlled. Through the optimization of expertise and available resources, the Division leverages its efforts to meet the needs with the greatest potential impact or otherwise indicated by our customers as high priority.

Since self-declaration of conformance in 2006, reassessed early in 2010, the Division has maintained compliance to the relevant requirements of ISO/IEC 17025 and ISO Guide 34 as part of the NIST quality system in our calibration services and production of our Standard Reference Materials (SRMs®). Details on our quality system, including our various procedures, are available on-line at http://www.nist.gov/pml/div682/qualitysystem.cfm.

The Division continues to be involved in international efforts, and several members are active participants in the three sections of the Consultative Committee on Ionizing Radiation (CCRI) as well as in our Regional Metrological Organization, the Sistema Interamericano de Metrología (SIM). We participate in comparisons of our national standards with those of other National Measurement Institutes (NMIs) to assure the quality of our measurement services and to satisfy the requirement that the U.S. standards are consistent with those of other NMIs and with the SI within stated uncertainties. Special priority is given to comparisons conducted under the auspices of the International Committee on Weights and Measures (CIPM) in support of the CIPM Mutual Recognition Arrangement; a listing of the over 100 ionizing radiation comparisons NIST has been involved in (more than 20 during the last 5 years) can be found at http://kcdb.bipm.org/AppendixB/KCDB_ApB_search.asp (search "ionizing radiation" for metrology area and "United States" for country). Through collaborations, interactions, and comparisons with our colleagues throughout the world, we are able to ensure customers that NIST calibrations are the best available and will be recognized outside the U.S. borders and provide the technical basis in the radiation sciences for international trade, commerce and regulatory affairs.

Lisa R. Karam
Gaithersburg, MD
December 2010

TECHNICAL ACTIVITIES

The research activities of the Ionizing Radiation Division can be broken out into three general categories:

- Radiation and neutron physics (including facilities, neutron characteristics, and decay physics)
- Research in metrology (neutron science, radionuclide metrology, and dosimetry; and research supporting international comparisons)
- Applied research (to support health care and medical physics, energy and environment, industry and manufacture, and safety and security)

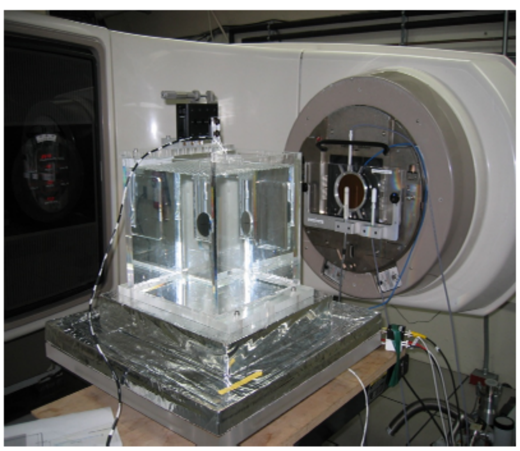
Research results are distributed to the larger community through a variety of mechanisms including publications, presentations, and measurement services (including calibrations and SRM®s). Listings of calibrations services (http://www.nist.gov/ts/msd/calibrations/ionizing-rad_index.cfm) and SRM®s [http://www.nist.gov/ts/msd/srm/ (key word: radioactive)] are available on-line.

Radiation and Neutron Physics: *providing the tools for radiation sciences*

Facilities and Methods

Accelerator Facilities

The Division's accelerator facilities continue to support a broad range of research efforts in the areas of industrial and medical dosimetry, homeland security, radiation-hardness testing and materials-effects studies. Topics of research during this reporting period included: (1) a broad-energy range calibration of charged-particle spectrometers used in space-flight applications, (2) calibration of a beta spectrometer which will be employed in a fundamental nuclear physics measurement of the neutron lifetime, (3) solar cell performance validation studies at several different electron energies and fluences, and (4) an international bi-lateral comparison of high-energy photon dose standards jointly conducted with the Bureau International des Poids et Mesures (BIPM).



Graphite transfer ionization chamber in a water phantom and monitor chambers attached to accelerator head for dose normalization. **(Photograph by: Fred B. Bateman)**

Many applications, including electron irradiation of solar cells, require that electron fluence be delivered to a group of perhaps 10 or 15 samples, and that the total fluence given to all the samples matches the target fluence. To help achieve these two requirements, a variable-speed radiation scanning system was developed which sweeps back and forth under the electron beam, thereby ensuring that all samples receive the same fluence. This system employs either one or two scanning arms to allow scanning in one or two dimensions, depending on sample size and uniformity requirements. A digital counter tracks the target charge measured by a Faraday cup and compares it to the actual charge at the end of each scan. The scan speed of the subsequent scan is then adjusted based on the ratio of the measured charge to the target charge. In this way, slow variations in accelerator output are compensated, resulting in the measured charge being within a few tenths of a percent of the target charge in most cases.

The Division's Clinac facility was recently employed in a series of bi-lateral comparisons of the NIST and the BIPM absorbed dose-to-water standards for high-energy accelerator photon beams. These comparisons, piloted by the BIPM, involve about 10 National Measurement Institutes (NMIs) which have a primary dose standard and a high-energy photon beam facility. In each case, the BIPM transports and sets up its own equipment at the participating NMI, and measurements are conducted using at least two photon beam qualities available at the accelerator facility of the respective NMI.

For the measurements conducted at NIST, comparisons were performed using 6 MV and 18 MV photon beams, at a maximum dose rate of 2.4 Gy/min. The NIST primary standard for high-energy photon dose is based on a water calorimeter, in which the small radiation-induced temperature rise in a water vessel is sensed by a thermistor and accurately measured by an AC Wheatstone bridge apparatus. Calorimetric techniques are also employed by the BIPM in their realization of high-energy photon dose; however, the BIPM system uses a calorimeter body made of graphite, and the dose conversion from graphite to water is achieved through the use of a transfer standard and Monte Carlo modeling.

These comparisons were motivated by a desire to demonstrate equivalence of high-energy dose standards between each NMI and the BIPM, and by extension, equivalence of the dose standards among the participating NMIs. Since high-energy photon facilities have almost completely replaced ^{60}Co sources for radiotherapy in industrialized nations, NMIs must develop, maintain and validate their high-energy photon standards. This international comparison provides a rigorous quality-assurance test, and adjustments can be made as needed to the technique or measuring apparatus employed by the NMI to ensure proper dissemination of absorbed-dose standards.

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X-Ray Standards

A new free-air ionization chamber has been built to eventually replace the Wyckoff-Attix chamber, which has been used at NIST as a primary x-ray standard for more than fifty years to realize air kerma for x-ray beams of 50 kV to 300 kV. The dimensions and the parallel-plate design of the new chamber are identical to those of the Wyckoff-Attix chamber, but the materials are different. The chamber incorporates a unique guard bar and insulator design, and precision slides facilitate alignment and direct measurement of the air-attenuation correction. The new standard will undergo a full evaluation in a parallel measurement arrangement with the current standard.

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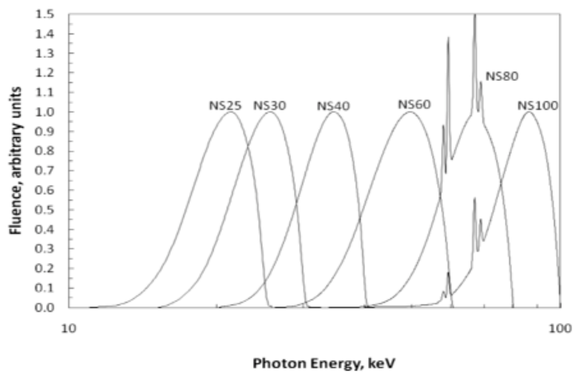
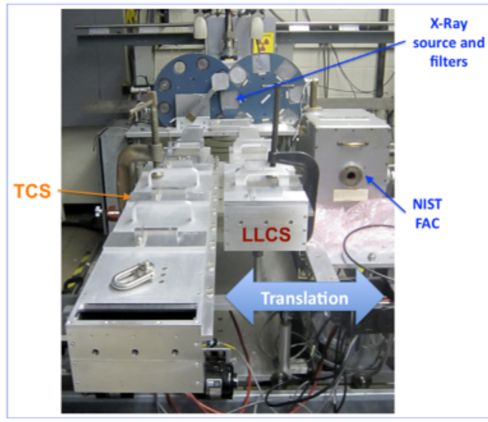
Spectrometry of X-Ray Beams Used for Calibrations

Spectrometry measurements in the x-ray calibration ranges have been undertaken using a high-resolution HPGe detector both in the direct beam and at 90° using a Compton-scatter spectrometer. Pulse-height distributions were obtained for all the NIST and International Organization for Standardization (ISO) beams produced by the NIST 100 keV and 300 keV x-ray generators, and have been unfolded and are in the process of being tabulated. This was performed for a number of narrow-spectrum beam qualities (shown below) and used to calibrate a wavelength-dispersive crystal x-ray spectrograph used by Lawrence Livermore National Laboratory (LLNL) to diagnose laser-to-x-ray conversion efficiencies of laser-produced plasmas.



Fits to newly-measured NIST narrow-band beam qualities after unfolding the spectra for detector response.



Calibration of two crystal spectrometers (TCS & LLCS) from LLNL. (Photograph by: Lawrence T. Hudson)

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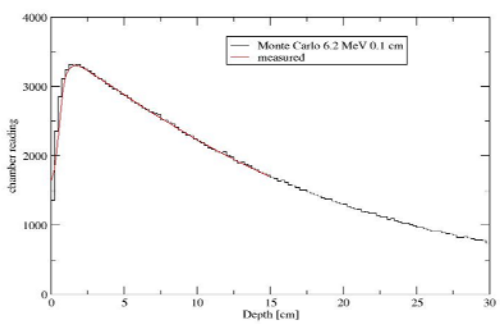
Metrology: *from the laboratory to quantitative measurements*

Metrology Research

Theoretical Dosimetry and Radiation-Transport Calculations

The radiation transport methods pioneered and developed at NIST to calculate the penetration of electrons and photons in matter are used in most of the major Monte Carlo simulation codes today. Monte Carlo simulation is increasingly applied to problems in radiation metrology, protection, therapy and processing as an accurate tool for design, optimization and insight often inaccessible to measurement. Our programs continue to develop and use Monte Carlo calculations for the understanding and refinement of our measurement standards, and for the many applications of ionizing radiation with which we are involved. Some examples of the application of Monte Carlo simulation to current problems in theoretical dosimetry or applications involving radiation include the development of a computational model of the NIST's Clinac 2100C medical accelerator for an international intercomparison of absorbed dose to water standards and the computation of wall corrections for an ionization chamber developed for direct realization of air kerma in high energy photon fields used in non-intrusive cargo inspection systems.



Comparison of Monte Carlo calculations to measurements of depth dose in a water phantom irradiated by the Clinac 2100C using the 6 MV photon mode.

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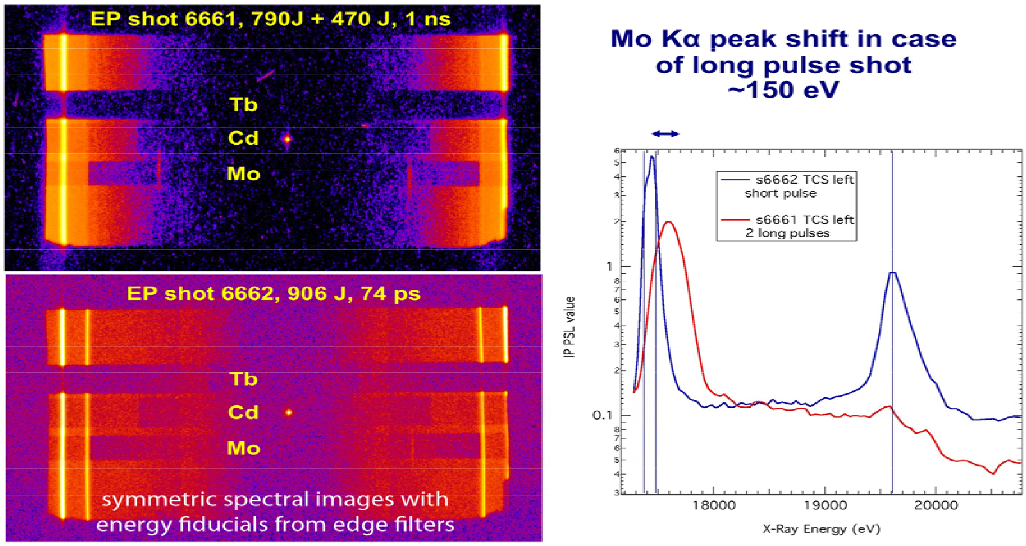
Applications of Diagnostic X-ray Spectrometers

The Radiation Interactions and Dosimetry Group designs, fabricates, and calibrates bent-crystal optics and diagnostic spectrometers for customers around the world. These have been fielded to help characterize the performance and x-ray spectra from advanced medical x-ray sources, laser-produced plasmas, terawatt pulsed accelerators, electron cyclotron resonance ion sources, electron-beam ion traps, intense ultrafast laser sources, and inverse-Compton backscatter sources. A recent model was developed and demonstrated at the Extended Performance laser of the University of Rochester's Laboratory for Laser Energetics (OMEGA-EP). The accompanying graphic demonstrates one diagnostic capability of these instruments. The Mo K spectral lines are shown to differ markedly from plasmas created with relatively short laser pulses (74 ps) compared to 1 ns irradiations. The broadening and shift to higher energy reveals the production mechanisms and the charge state(s) of highly charged ions under long-pulse irradiation; the narrow lines produced with picosecond pulses were found to be from neutral species (too fast for ion production).



Spectrometer images (left) and column summed Mo K spectra (right) from nanosecond and picosecond pulse laser irradiation of a molybdenum target.

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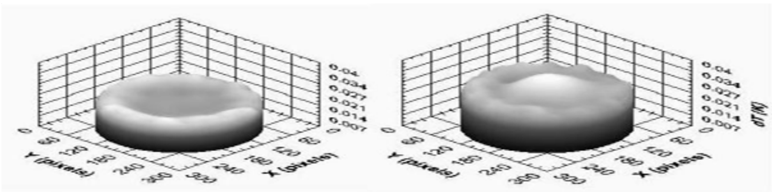
Advances in Water Calorimetry

The NIST water calorimetry effort has been directed toward accurate modeling and detailed measurement of time-varying phenomena within the calorimeter vessel – due principally to heat transfer – with the objective of developing primary standards that address metrological challenges posed by modern radiotherapy beams. The work has had two primary thrusts:

Photograph of the transducer array for ultrasound tomography. (Photograph used with permission from Luna Innovations, LLC.)

1) Continue work on a second-generation, Domen-type primary standard for standard reference ^{60}Co and high-energy x-ray beams. Procedures developed for obtaining heat-transport correction factors for the second-generation, Domen-type instrument have been tested successfully under a variety of irradiation conditions in ^{60}Co beams. Comparison tests of this instrument with ionization chambers calibrated via the original water calorimeter have shown agreement to within 0.3 %, which is well within the experimental uncertainty of ± 0.47 % associated with the historical value. Further tests are being conducted in both ^{60}Co and high-energy x-ray beams provided by our Clinac 2100C medical accelerator.

2) Develop a high-precision thermometry system for water based on ultrasonic time-of-flight technology that would leverage the imaging capabilities of ultrasound to enable dosimetry of time-varying, 3D dose fields in water from arbitrary types of beams. An ultrasonic thermometry technology, developed by Luna Innovations as part of a phase-II SBIR contract with NIST, has



Tomographic reconstruction of the temperature profile in water created by a laboratory heat lamp switched off (left) and on (right). The structures on the periphery are reconstruction artifacts. The dome in the middle represents an 8 mK temperature rise.

progressed from a single-channel implementation capable of resolving radiation-induced average temperature changes with microkelvin-level precision along a 30 cm diameter of a water phantom to a multi-channel array instrument that uses tomographic reconstruction to obtain time-resolved, 2D temperature distributions with a spatial linear resolution of better than 5 mm. Preliminary studies with the multi-channel instrument yielded sub-millikelvin resolution of temperature changes induced in water by radiation from a heat lamp. Because it is based on the same technology used in the single-channel prototype, much higher temperature resolution (microkelvin) is expected to be achievable. The multi-channel array was recently acquired by NIST so that further research may be conducted to investigate its feasibility for use in radiation dosimetry.

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Advancing Alanine Dosimetry for Small Radiosurgery Fields

Research is underway to expand the current range (20 Gy to 200 kGy) of alanine dosimetry to include therapy level dosimetry (as low as 1 Gy) for small-field radiation treatment applications (*e.g.*, TomoTherapy or GammaKnife). The Hi-Art TomoTherapy System (TomoTherapy, Inc.), for example, uses a rotating linear accelerator to deliver a fan of small beamlets in a helical pattern. This next generation of cancer therapies is growing rapidly to address demand for radiation treatment of the more than one million new cancers per year in the United States.

However, these improvements in radiotherapy pose interesting challenges for the dosimetry systems available for TomoTherapy certification. Typically, traceability to national standards is achieved by transfer dosimetry with ion chambers from a calibration laboratory. However, ion chambers are not well-suited to this task due to the small size of each beamlet.

Also, as the beam number increases in radiotherapy treatments, the dose delivered per beam decreases; this poses sensitivity/measurement challenges. NIST is working with the dosimeter manufacturer (Gamma Service) and the measurement instrument manufacturer (Bruker BioSpin) to adapt the dosimeter and spectrometer to this new application. Collaborations are underway with the Department of Radiation Oncology, University of Pittsburgh Cancer Institute, and the Radiology and Radiological Sciences Department of the Uniformed Services University of the Health Sciences.

Leksell Gamma Knife (LGK) International Calibration Survey In partnership with the Department of Radiation Oncology and Neurological Surgery, University of Pittsburgh Medical Center, NIST is providing measurement support for a survey of approximately 100 Leksell Gamma Knife (LGK) units worldwide to gather detailed information about calibration procedures, measure the output of the surveyed LGK units using alanine dosimeters, and compare these results with the user's calibration. To date, 45 LGK units from 43 different centers in 12 different countries have participated in this project (23 from North America, 11 from Europe, and 11 from Asia). The deviations observed between the LGK user's calibration and the alanine dosimetry measurements were small with a mean value of 1.4 %. All 45 LGK units were within 5 % and 43 (96 %) LGK units were within a 3 % deviation. Different calibration protocols are used worldwide (North America AAPM TG-21, Europe and Asia IAEA TRS398). A small (1.4 %) but systematic deviation is observed for LGK centers in Europe and Asia where the IAEA TRS398 protocol is used. This deviation can be explained by considering the ABS plastic calibration phantom to be water equivalent when performing calibrations in Europe and Asia. Very good overall agreement between a user's reported calibration and alanine dosimetry measurements was observed so far in this study.

Dosimetry System Advancements The Electron Paramagnetic Resonance (EPR) dosimetry facility and the gamma-ray irradiators that support the alanine dosimetry system are unique in design and capabilities. Recently, these capabilities were further advanced through an MOU that was signed between NIST and the Uniformed Services University of the Health Sciences to transfer a state-of-the-art EPR spectrometer to NIST for collaborative research. In addition to the spectrometer upgrade, small-field dosimetry advancements for the alanine dosimetry system are being made by working with the dosimeter manufacturer (Gamma Service) to produce 2 mm and 3 mm dosimeters and the spectrometer application specialists (Bruker Biospin) to develop new measurement protocols for dosimetry below 10 Gy. Samples of 2 mm and 3 mm alanine dosimeters were supplied to NIST for testing. These were irradiated to doses from 0.5 Gy to 50 Gy and tested at Bruker Biospin with a new analysis protocol that was based on a newly designed *in situ* EPR-internal reference assembly with a proprietary EPR intensity reference material (a copy of this device was loaned to NIST for future testing) and a spectral analysis routine based on spectral least-squares fitting. The first impressions of these advancements were that the 3 mm dosimeters may be useful in the 2 Gy to 4 Gy range at a minimum; measurements at 1 Gy could be possible. The 2 mm dosimeter may be limited to doses above 10 Gy.

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International Comparisons for Air Kerma and Absorbed Dose to Water from Gamma-ray Beams

A bilateral comparison was conducted between NIST and the International Atomic Energy Agency (IAEA) to support international efforts for harmonizing radiation protection measurements around the world, ensuring the safety of radiation workers and the public. The air kerma national standards from ^{137}Cs and ^{60}Co beams were compared at both the IAEA and NIST. The work started in the second half of 2009 and was completed in January 2010. Two reference class chambers with volumes of 100 cm^3 and 1000 cm^3 owned by the IAEA were used during the comparison. Calibration coefficients for the two chambers were determined at NIST and at the IAEA in both ^{137}Cs and ^{60}Co beams. A quite good agreement of within less than 0.30 % for the air kerma from both gamma-ray beams was obtained. In April 2010 the results of the EUROMET key comparison project 813 were published in a special issue of *Metrologia*. This work supports international efforts for harmonizing radiation measurements that are routinely made in the medical field. NIST represented the U.S. as one of 26 countries that participated in this long term project that was carried out over a period of 4 years and was completed at the end of 2008. The radiation quantities absorbed dose to water and air kerma from ^{60}Co gamma ray therapy level beams were compared in a blind test format. In addition, NIST served as the host laboratory for participants in the Sistema Interamericano de Metrología (SIM) regional metrological organization comprised of national standards laboratories in the American continent. The results of this work are also available from the BIPM Key Comparison Database (http://kcdb.bipm.org/AppendixB/KCDB_ApB_search.asp) under comparison identifiers EUROMET.RI(I)-K1 and EUROMET.RI(I)-K4.

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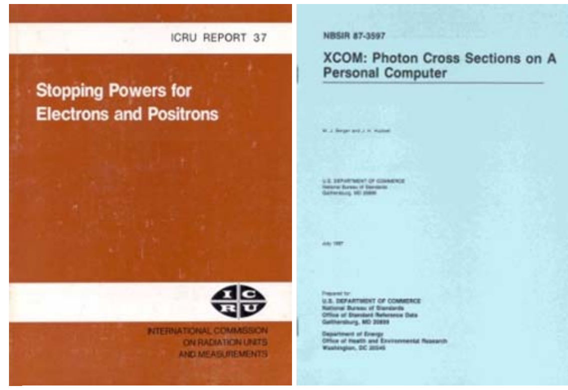
Calibrations and Standards *("Measurement Services")*

Standard Reference Data on Radiation Interactions



ICRU Report 37 (left) and NBSIR 87-3597 (right).

NIST has nearly five decades of experience in the development of critically evaluated, comprehensive databases of cross-section information for ionizing photons (x and gamma rays), electrons, and heavy charged particles. These data are often adopted by national and international standards organizations for use in radiation protection, medical therapy, and industrial applications. This work continues in the Division's Photon and Charged-Particle Data Center. The compilations of the Data Center rely heavily on evaluating measurements and on their synthesis with available theory to extend the data and provide for comprehensive coverage over broad ranges of energy and materials. The quality of the work of the Data Center is reflected in the many requests for our data from other laboratories and in the use of our data in many computer codes, engineering and scientific compendia, books and review articles, and in the reports and protocols of national and international standards organizations. Each year we respond to inquiries from the medical, industrial, academic, government, and other scientific communities for technical information and data. We also participate as consultants to or as members of committees that evaluate the best available data for particular applications. For example, we are currently serving on a committee for the International Commission on Radiation Units and ICRU Report 37 (left) and NBSIR Measurements (ICRU) that is expected to produce a report on key physical data for use in dosimetry applications. With the help of the NIST Physical Measurement Laboratory's Office of Electronic Commerce in Scientific and Engineering Data, a number of the Center's databases can be accessed on the worldwide web.

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Calibrations of Radiation Measuring Instruments in ^{137}Cs and ^{60}Co Gamma-ray Beams

The Radiation Interactions and Dosimetry Group maintains and disseminates the national measurement standards for air-kerma (exposure) from ^{137}Cs and ^{60}Co gamma-ray beams and for absorbed dose to water from ^{60}Co gamma-ray beams. The dissemination of the primary standard is performed via calibration of gamma-ray measuring instruments using one of seven gamma-ray irradiator sources. These calibration facilities provide a range of air-kerma and absorbed dose to water rates that help to serve a large number of users: two ^{137}Cs sources provide air-kerma rates from 4 mGy/h to 90 mGy/h; a third ^{137}Cs source provides air-kerma rates of 2 Gy/h and 3 Gy/h; two ^{60}Co sources provide air-kerma rates from 0.1 mGy/h to 1 mGy/h; and two ^{60}Co tele-therapy-level sources provide absorbed dose to water and air-kerma rates of 26 Gy/h and 6 Gy/h, respectively. The NIST standards are disseminated routinely through a number of U.S. secondary standard instrument calibration laboratories. These include the three Accredited Dosimetry Calibration Laboratories (ADCLs) that are accredited by the American Association of Physicists in Medicine (AAPM), military secondary calibration facilities, the U.S. DOE, state laboratories, instrument manufacturers, nuclear power plants and U.S. customs.

Gamma-ray calibration facilities.
(Photographs by: Ronaldo Minniti.)

Setup of absorbed dose to water measurement.
(Photograph by: Ronaldo Minniti.)

Proficiency tests of the AAPM ADCLs for the measurement of air-kerma and absorbed dose to water from ^{60}Co gamma-ray beams were conducted during the first part of 2009. An A12 chamber was used. Excellent agreement, within less than 0.3 % for the air kerma tests and 0.2 % for the absorbed dose to water tests, was obtained between the NIST and all the ADCLs. This is the third round of proficiency tests conducted for air-kerma from ^{60}Co gamma-ray beams between the NIST and the ADCLs since the re-characterization of the NIST ^{60}Co gamma-ray beams in terms of air-kerma that was completed in 2003. The first proficiency test was conducted in early 2004, which resulted in a similar level of agreement to that obtained in 2009.

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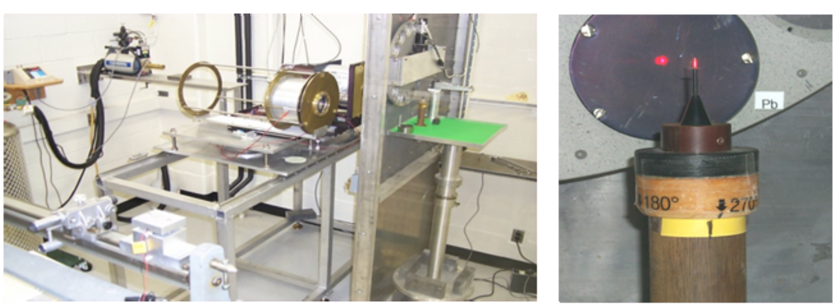
Applied Research: *from the laboratory to the customer*

Health Care and Medical Physics

Calibration of Low-Energy Photon Brachytherapy Sources

Small radioactive "seed" sources used in prostate brachytherapy, containing the radionuclide ^{103}Pd, ^{125}I, or ^{131}Cs, are calibrated in terms of air-kerma strength using the NIST Wide-Angle Free-Air Chamber (WAFAC). The WAFAC is an automated, free-air ionization chamber with a variable volume, allowing corrections to be made for passage of the beam through non-air-equivalent electrodes. In the past decade, over 1,000 seeds of 40 different designs from 18 manufacturers have been calibrated using the WAFAC. On-site characterization at seed manufacturing plants for quality control, as well as at therapy clinics for treatment planning, relies on well-ionization chamber measurements. Following the primary standard measurement of air-kerma strength, the responses of several well-ionization chambers to the various seed sources are determined.

The ratio of air-kerma strength to well-chamber response yields a calibration coefficient for the well-ionization chamber for a given seed type. Such calibration coefficients enable well-ionization chambers to be employed at therapy clinics for verification of seed air-kerma strength, which is used to calculate dose rates to ensure effective treatment planning. To understand the relationship between well-ionization chamber response and WAFAC-measured air-kerma strength for prostate brachytherapy seeds, emergent x-ray spectra are measured with a high-purity germanium (HPGe) spectrometer. Knowledge of seed spectra allows separation of well-ionization chamber response effects due to spectrum differences from those due to seed internal structure and self-absorption, which influence the anisotropy of x-ray emissions from the seed. The relative response of calibration instruments has been observed to depend on such anisotropy.



*WAFAC calibration range, showing original and automated WAFACs, as well as the high-purity germanium (HPGe) detector (left panel). Close-up view of a seed (illuminated by a laser), mounted vertically on a rotating post, ready for calibration (right panel).(*Photographs by Michael G. Mitch)

Seed manufacturers periodically send batches of three to five seeds to NIST for calibration. These seeds are then forwarded to several Accredited Dosimetry Calibration Laboratories (ADCLs) to establish and subsequently maintain the secondary standard at these laboratories for use in calibrating clinical well-ionization chambers. To ensure that seeds submitted for WAFAC calibration are consistent and representative of that particular seed design so that associated errors will not be propagated down the traceability chain to the ADCLs, seed manufacturers, and therapy clinics, several additional tests have been implemented. The distribution of radioactive material within a seed is mapped using radiochromic-film contact exposures. The in-air anisotropy of seeds is studied by taking WAFAC and x-ray spectrometry measurements at discrete rotation angles about the long axis and the axis perpendicular to the mid-point of the long axis of the seed, respectively. The "air-anisotropy ratio", calculated from the results of angular x-ray measurements, has proven to be a useful parameter for explaining differences in well-chamber response observed for different seed models having the same emergent spectrum on their transverse axis.

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Evaluation of Uncertainty in Brachytherapy Dosimetry

NIST is participating in Task Group # 138 (TG-138) of the American Association of Physicists in Medicine (AAPM), AAPM Recommendations on Assessing Uncertainty of the Brachytherapy Clinical Dose Evaluation Process. The goal of TG-138 is to assess the birth-to-death process of brachytherapy source manufacture, dosimetry, calibrations, treatment planning, and clinical implementation by identifying sources of uncertainty towards quantifying realistic clinical evaluation of treatments. NIST is in a unique position to contribute to this effort by analyzing ionization chamber, source anisotropy, and x-ray spectrometry data collected on hundreds of prostate brachytherapy seeds over the past several years. Sources of uncertainty that influence the chain of traceability of the NIST primary air-kerma strength standard to the clinics via secondary calibration laboratories will be identified and quantified, including those due to batch-to-batch variability of the physical properties of seeds.

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The Development of New Reference Standards for Digital Mammography

With the introduction and Food and Drug Administration (FDA) approval of mammography units using a tungsten (W) anode with either a silver (Ag) or rhodium (Rh) filter, there are new concerns about air kerma, dose and non-invasive kVp measurements. The response of ionization chambers in the 20 kV to 40 kV mammography energy range is relatively flat. However, the FDA is concerned that if a solid-state air-kerma measuring device is used that is not calibrated in the appropriate energy spectrum, dose errors will result. The new NIST reference mammography beams using a tungsten target and silver, rhodium, molybdenum (Mo) and aluminum (Al) filters at 20 kV to 50 kV will provide FDA inspectors, chamber manufacturers and calibration facilities with the techniques that best represent the new beams used in clinics. It may be possible in the near future for NIST to provide kV calibrations for non-invasive kVp meters, which are commonly used to measure the kV and half-value layer (HVL) on clinical units. These new reference standards will be available for calibrations and the FDA-MQSA proficiency tests. The 100 kV x-ray unit will be used for all the new techniques. The kV has been fully calibrated using NIST-traceable voltage dividers. The beam parameters will be the same as those techniques supported by the Physikalisch-Technische Bundesanstalt (PTB), the German standards laboratory, giving U.S. manufacturers the ability to get their chambers calibrated in the U.S. and distribute them within Europe.

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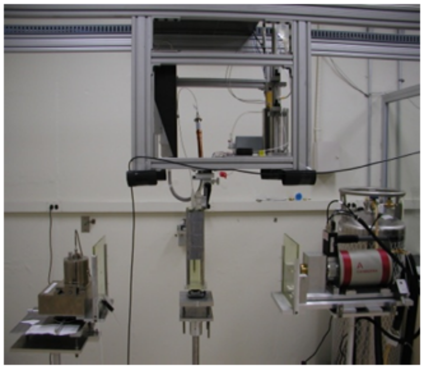
Calibrations of a Miniature X-Ray Source Used for Electronic Brachytherapy

A new laboratory dedicated to establishing a national primary air-kerma rate standard for Xoft's AXXENT™ miniature x-ray source has been fabricated. The Xoft source was designed to provide low-energy x-rays (< 50 keV) for use in brachytherapy. The air-kerma rate is being directly realized through use of the Lamperti free-air chamber, which was compared with another national x-ray standard with these sources. A high-purity germanium (HPGe) x-ray spectrometer is used to monitor the energy spectrum of the beam in real time, as well as provide necessary input data for Monte Carlo calculations of correction factors for the free-air chamber. To account for spatial anisotropy of emissions, the free-air chamber and spectrometer are rotated about the long axis of the x-ray tube during measurements. The response of well-ionization chambers to the x-ray sources is being studied in preparation for the development of a measurement assurance program for the dissemination of the new NIST standard to Accredited Dosimetry Calibration Laboratories (ADCLs). The ADCLs are accredited by the American Association of Physicists in Medicine (AAPM), and calibrate radiation measuring instruments for use in therapy clinics.



Xoft AXXENT™ electronic brachytherapy source in NIST lab (Photograph by: Michael G. Mitch)

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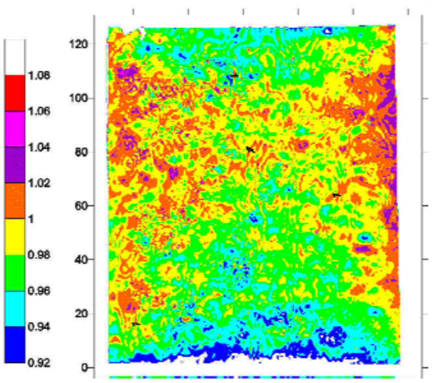
Absorbed-Dose Measurements to Support Biologics Research

The Radiation Interactions and Dosimetry Group has been working with Maryland-based biotech firm Sanaria Inc. that is planning to manufacture a new vaccine against malaria. Production of the new vaccine involves irradiating mosquitoes containing the parasite Plasmodium falciparum, the most dangerous species of parasite that causes malaria. Specifically, the Group performed measurements to assist Sanaria in assuring a minimum delivered dose of 150 Gy to all mosquitoes in the Sanaria ^{60}Co irradiator. This was followed by dose-mapping measurements to give details on relative dose uniformity for the entire volume of the irradiation vessel that would hold mosquitoes. Then a series of experiments were done to determine the ratio between doses for dosimeters placed in the minimum-dose position inside the vessel versus dosimeters placed on the outside surface of the vessel. The successful determination of this ratio and its statistical uncertainty formed the basis for the vaccine manufacturing process quality assurance measurements. The first round of human clinical trials was successful and preparation is underway for the second round manufacturing process quality assurance measurements. The first round of human clinical trials was successful and preparation is underway for the second round.



Dose map of mosquito irradiation vessel.

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Applications of NIST Alanine/EPR Dosimetry to the Irradiation of Blood and Blood Products

At present, gamma irradiation of blood products is the only procedure known to prevent transfusion-associated graft-versus-host disease (TA-GVHD). The most common irradiation sources used are ^{60}Co and ^{137}Cs. Most blood centers rely on a nominal dose of 25 Gy with no less than 15 Gy delivered to any area of the bag for these radiation beams to inactivate lymphocytes in cellular products for transfusion. International Specialty Products (ISP) is a commercial manufacturer of a variety of film products that are used for the verification of irradiation of blood or validation of a blood irradiator's performance.

In 2004, NIST was contacted by ISP about the possibility of using alanine dosimetry to provide traceability of the ISP dose-mapping service for blood irradiators to national standards. Throughout the several years of experience with dosimetry measurements at this relatively low range for the alanine system, adaptations and refinements have led to a protocol that will be incorporated into the existing alanine transfer dosimetry service. On a near weekly basis, NIST continues to provide measurement services of alanine dosimeters that have been co-located with ISP films in blood-irradiator canisters.

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Energy and the Environment

Comparison of ^{60}Co Absorbed Dose for High-Dose Dosimetry

NIST participated in a recent international comparison of standards for absorbed dose to water for ^{60}Co gamma radiation at radiation-processing dose levels organized by the Bureau International des Poids et Mesures (BIPM), CCRI(I)-S(2). At the request of NIST, the comparison was preceded by a NIST-led comparison to demonstrate NIST-recommended modifications to the BIPM protocol. The NIST comparison demonstrated the need to know the participant's calibration scheme and dose rates, as well as the inclusion of an additional dose level (1 kGy, in addition to 5 kGy, 15 kGy, and 30 kGy). The rationale for modifying the protocol was based on the recent NIST characterization of a rather obscure and previously unknown dose rate effect in alanine. The effect was such that its greatest impact was on National Measurement Institute (NMI) metrology. The discovery of this effect and its contribution to international comparison data is a demonstration of the quality of NIST measurement capabilities and associated facilities, and is a direct result of the quality system being implemented at NIST in the last decade.

Eight laboratories offering high-dose irradiation services took part in the comparison; the Czech Metrology Institute Inspectorate for Ionizing Radiation (CMI-IIR, Czech Republic), the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti (ENEA-INMRI, Italy), the Laboratoire National Henri Becquerel (LNE-LNHB, France), the National Institute of Metrology (NIM, China), the National Institute of Standards and Technology (NIST, USA), the National Physical Laboratory (NPL, UK), the High Dose Reference Laboratory of the Danish Technical University (Risø-HDRL, Denmark) and the Institute for Physical-Technical and Radiotechnical Measurements, Rostekhregulirovaniye of Russia (VNIIFTRI, Russian Federation). All laboratories hold primary standards with the exception of the CMI-IIR and the Risø-HDRL that hold secondary standards traceable to the International Atomic Energy Agency (IAEA) and the National Physical Laboratory (NPL), respectively. In addition, the BIPM, although it does not offer a high-dose service, took part at the lowest dose level (1 kGy) to provide a direct link to the international reference for absorbed dose to water in ^{60}Co. Two transfer dosimeters were used for the comparison; the alanine/ESR dosimetry system of the NIST and that of the NPL.
These eight national standards for absorbed dose to water in ^{60}Co gamma radiation at the dose levels used in radiation processing were compared over the range from 1 kGy to 30 kGy using the alanine dosimeters of the NIST and the NPL as the transfer dosimeters.

It was found that the national standards are in general agreement within the standard uncertainties, which are in the range from 1 to 2 parts in 10^2. The dose-rate effect was observed at the highest doses for the laboratories that used low-rate gamma sources. A final report is in preparation.

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Industrial Applications

A Study of the Irradiation-Temperature Coefficient for Alanine Film and Pellet Dosimeters at Elevated Temperatures

Correcting the response of a dosimeter for the average temperature during irradiation processing improves the accuracy of the dose measurement. The relationship between the dosimeter's radiation response to the absorbed dose and its temperature during irradiation is termed the irradiation-temperature coefficient, typically expressed in percent change per degree. The temperature rise in dosimeters irradiated with high-intensity ionizing radiation sources can be appreciable. This is especially true for electron-beam processing in which dosimeter temperatures can approach 80 °C. However, the temperature coefficients determined for commercial dosimeters have been characterized only up to ≈ 50 °C. The first NIST study revealed modest (0.5 % to 1.0 %) deviations from the predicted value at temperatures above 70 °C for absorbed doses of 1 kGy and 20 kGy. However, these data were inconsistent with a National Physical Laboratory (NPL) manuscript published coincidently that attempted to address the same topic. Though similar in nature, the NPL study used dosimeters from a different manufacturer and of a different experimental design. The NPL study found significant deviations from linearity in the alanine temperature responses that were dose dependent. A follow-up study by NIST was undertaken to resolve this discrepancy. This study co-irradiated alanine dosimeters from each manufacturer used by NIST and NPL over a wide range of absorbed doses and irradiation temperatures. The NIST study found that though there was a slight variation in the temperature coefficient between the two alanine dosimeter sources (a finding that was expected), both systems were linear with irradiation temperature up to 70 °C and the NPL observations of non-linearity were not reproduced. It was presumed that the NPL findings of non-linearity resulted from their experimental design. These data confirmed that there is no fundamental difference in the two commercial alanine dosimeter sources and that temperature corrections could be made on industrial irradiations at the extremes of irradiation temperature and absorbed dose.

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Dose/Dose-Rate Effects in Alanine Dosimetry

Check standards are used by the NIST Ionizing Radiation Division to monitor the performance of the alanine dosimetry system that is central to its high-dose transfer dosimetry service. These measurements are performed to confirm the operational readiness of the calibration curve. Deviations from the expected check standard values can result from a wide range of sources that include manufacturing abnormalities in a dosimeter and spectrometer-related changes. A few years ago, check-standard measurement deviations unveiled a previously unknown rate effect for the alanine dosimetry system. This rate-effect study characterized a complex relationship between the radiation chemistry of crystalline alanine and the applied dose rate that was also dependent on the absorbed dose. That the rate effect only becomes significant above 5 kGy likely contributed to it only recently being discovered despite decades of research in alanine dosimetry. It was learned that the effect is intrinsic to alanine and is not dependent on the chemical form or manufacturing formulation of the alanine dosimeter. The study postulated that the production of one (or more) of the radiation-induced alanine radicals is dependent on the dose rate.

A follow-up study aimed to investigate the influence of irradiation temperature on the dose rate effect. No increase in the effect was found with increasing temperature, but the dose rate effect appeared to be nonexistent at irradiation temperatures of -10 °C and -40 °C.

In summary, it is known from this work that:

- the rate effect is estimated to be
  - zero at dose rates above 2 Gy/s
  - significant at some value below 2 Gy/s, and
  - clearly measurable at 1 Gy/s
- the rate effect depends on absorbed dose, it

- is not measurable at 1 kGy or less
- becomes significant above 5 kGy
- reaches a maximum effect at about 30 kGy

- for doses above 5 kGy, the magnitude of the effect is not dependent on the relative values of the high and low rates compared, but rather only on whether the two rates compared fall above 2 Gy/s and below 1 Gy/s. If dosimeters irradiated with dose rates from either of these two categories are compared the effect is measureable, and if the dose is above 30 kGy the effect is maximized.

Experiments are planned to map the dose rate effect across the 1 Gy/s to 2 Gy/s transition range.

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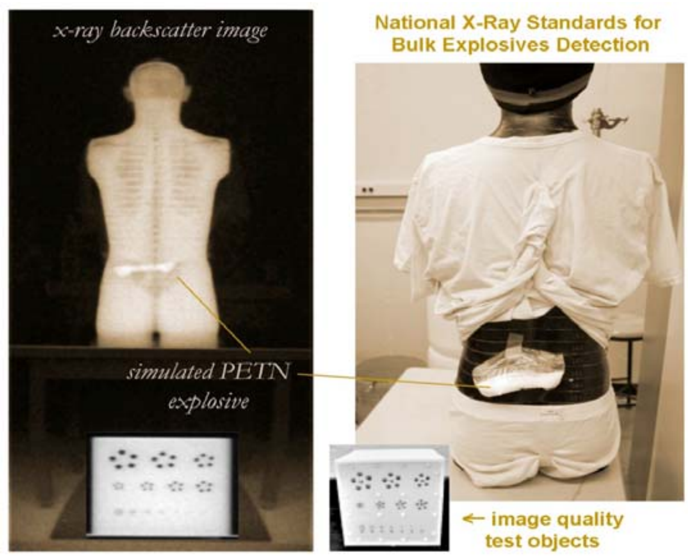
Homeland Security

X-Ray Security-Screening Standards for Homeland Security

With support from the Department of Homeland Security (DHS), the Radiation Interactions and Dosimetry Group facilitates the development and maintains technical-performance standards for five classes of x-ray security-screening systems that are used to detect bulk explosives and other illicit items: checkpoint cabinet, computed tomography, cargo/vehicle, human subjects, and left-behind objects (bomb squads). American National Standards Institute (ANSI) and International Electrotechnical Commission (IEC) working groups have been organized to develop standards for both radiation safety and technical performance, particularly image quality. The designations and current versions are shown in the table.

Venue	Technical Performance	Radiation Safety
Checkpoint	ANSI N42.44 – 2008 ASTM F 792 – 2008	ASTM F 1039 (21 CFR 1020.40)
CT / EDS (checked luggage)	ANSI N42.45-2010	(21 CFR 1020.40)
Cargo / Vehicle	ANSI N42.46 – 2008 IEC 62523 – 2010 ANSI N42.41 – 2007	ANSI N43.16 – draft IEC 62523 – 2010 ANSI N43.14 – draft
Whole Body Imaging (AIT)	ANSI N42.47 – 2010 IEC - CD	ANSI/HPS N43.17 – 2009 ANSI/ANS 6.1.1 IEC 62463 – 2010
Bomb Squads (portable sources)	NIJ 0603.01	ANSI/HPS N43.3

Table of national and international x-ray and gamma-ray security screening standards developed by the Division for imaging systems intended primarily for bulk-explosives detection.



X-Ray images of ANSI N42.47 test object and anthropomorphic phantom (left) and corresponding photographs (right) (Photograph by Lawrence T. Hudson)

These projects produce test methods and x-ray test pieces appropriate for the application; in some cases minimum performance requirements are quantified. This year the ANSI N42.45 and ANSI N42.47 standards were completed and formally accepted through the Institute of Electrical and Electronics Engineers (IEEE) balloting process as well as two IEC standards related to cargo and whole-body imaging systems. A set of ANSI N42.45 test objects was fabricated for distribution to U.S. international partners in aviation security.

In related work, the group maintains a test bed for assessing the image quality of portable x-ray and imaging systems used by bomb squads for explosives and ordinance detection and for disarmament. The results of testing will be used to establish minimum image-quality standards and update a National Institute of Justice standard covering these systems. This facility has recently been augmented with an x-ray screening system of the type used in prisons and airports to scan humans without physically removing their clothing. These tools were employed to support the response of DHS in the aftermath of the 2009 Christmas-Day bombing attempt (see accompanying photo).

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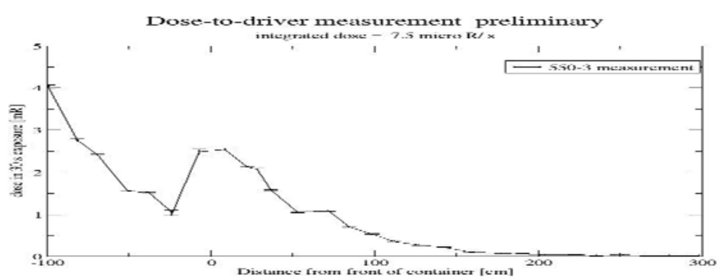
Advanced X-Ray Systems for the Detection of Special Nuclear Materials

The Radiation Interactions and Dosimetry Group provides support to the Domestic Nuclear Detection Office (DNDO) of the Department of Homeland Security (DHS) for their advanced non-intrusive inspection (NII) initiatives. Our support for these programs falls into three categories. The first category is to develop and implement methods to perform radiation dosimetry in and around these high-energy systems. The second thrust is to develop experimental designs, with our colleagues in the NIST Statistical Engineering Division, to evaluate the performance of these systems in terms of pass/fail trials for detection of threat surrogates and using the test methods specified in ANSI N42.46 for image quality. The NIST team also provides on-site support during testing as well as post-test analysis. The third area is to consult on other issues related to this type of equipment.



X-ray image taken by: Paul Bergstrom

The high-energy photon beams typically utilized in next generation NII systems present dosimetry challenges, as they are of markedly different character compared to those employed in the past. Hence, the methods developed by health physicists to perform dosimetry are of questionable validity. We have developed methodologies to perform measurements of dose to drivers of conveyances under inspection, to evaluate dose to cargo and inadvertent occupants of the conveyance and to determine the radiation footprint of these systems. We have applied these methods to 3 distinct NII systems in a series of tests.

The American National Standards Institute (ANSI) standard for the image quality indicators of non-intrusive cargo and a vehicle inspection system, ANSI N42.46, was previously developed through a series of meetings hosted by NIST. Application of the test methods described in the standard may not lead to a clear distinction between the performances of different systems. We have developed experimental designs and suggestions that have been, in part, adopted by the DNDO to lend rigor to these tests. We have also provided substantial input into the development and interpretation of tests of the pass/fail detection of threat surrogates (not a part of ANSI N42.46). Several test events have taken place and NIST has participated in the field and contributed analysis to the reports describing these events.

Finally, we investigate and provide advice on other effects that could result from deploying such equipment. Such advice is provided based on computations and/or measurements. These effects include compatibility issues with other equipment.
Dose to the driver of a truck (top) and image of the contents of a cargo container (bottom) being scanned by a high-energy non-intrusive inspection system.

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Air Kerma Measurements in High Energy X-Ray Beams

In the past few years there has been an increase in the deployment of x-ray screening systems at security checkpoints around the U.S. These systems are designed to detect potential threats that may be present in cargo containers and vehicles that pass through country borders. X rays are used for imaging the contents of vehicles and cargo. Because of the need to penetrate through the thickness of the wall of containers and vehicles in addition to the objects contained within, these systems rely on the use of penetrating radiation such as high energy megavoltage x rays with peak voltages of at least 5 MV.

The NIST prototype cavity chamber used to determine air-kerma rates.(Photograph by: Ronaldo Minniti)

As with any radiation device, users need to know the radiation doses involved and potential exposures to people. There are currently no national standards for megavoltage x-ray beams. As a result there are no explicit protocols on how to calibrate radiation measuring instruments to determine the air kerma delivered by these x-ray units. The Radiation Interactions and Dosimetry Group at NIST has initiated an effort to develop a protocol to calibrate instruments for high energy megavoltage x-ray beams. As a first step in this direction, a prototype cavity chamber has been developed that will allow the direct realization of air kerma from megavoltage x-ray beams. The instrument was designed and constructed at NIST and assembly was completed in the spring of 2010. Further investigations are underway for realizing the quantity air kerma and providing traceable measurements to users of x-ray based security screening systems.

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Validation of ANSI Standard N42.49

The American National Standards Institute/the Institute of Electrical and Electronic Engineers (ANSI/IEEE) N42.49 documentary standard was developed to meet the needs of emergency responders. In 2009, the Radiation Interactions and Dosimetry Group performed measurements in support of the development of the new standard. Radiation detectors including Personal Emergency Radiation Detectors (PERDs), radiochromic film cards and thermoluminescent dosimeters (TLDs) were used to validate a subset of the radiological test requirements listed in the ANSI/IEEE N42.49 standard.

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Safety and Worker Protection

Development of a New ^{137}Cs Gamma-ray Calibration Facility

Development of a new facility for the dissemination of the air kerma standard from ^{137}Cs beams has begun, which will allow extending the current range of air kerma values available at NIST. The design includes a new ^{137}Cs irradiator, safety and security systems, and a track positioning system for various types of radiation measuring instruments. The construction will be performed in two phases starting in early 2011. During the first phase the room will be equipped with radiation shielding and a security system. During the second phase the irradiator and positioning tracks will be installed. The new facility will allow dissemination of the national standard for a new range of air kerma values and will be available to existing as well as new customers including the U.S. Navy, U.S. Army, U.S. Air Force, Department of Energy, hospitals, clinics, nuclear power plants, and manufacturers of instruments.

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Calibration of Beta-Particle Sources and Instruments for Radiation Protection

A calibration service for protection-level beta-particle sources and instrumentation has been in place at NIST for several years. The measurement system is automated and capable of measuring extremely low absorbed-dose rates. The second-generation beta-particle secondary-standard system (BSS2), which includes the isotope ^{85}Kr, is utilized routinely for calibrations and research into standard extrapolation-chamber data-handling techniques. The sources were calibrated both at the Physikalisch-Technische Bundesanstalt (PTB) and at NIST, allowing a direct intercomparison of calibrations. The standardized techniques developed at PTB and NIST have been implemented in the NIST protection-level beta source and instrument calibration services.

Primary contact(s):

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NIST Work in Support of the Navy Dosimetry Program

TLD Model DT-702
Photograph by:
Ronaldo Minniti

During the last 2 years, NIST has helped the U.S. Navy transition to a new dosimetry system by providing dosimeter irradiations in ^{137}Cs gamma-ray beams. The new dosimetry program relies on the use of the model DT-702 thermoluminescent dosimeter (TLD) system. As a result, the older dosimetry program that relied on the use of a calcium fluoride solid-state dosimeter, the TLD model DT-526, was terminated. The monitoring of radiation exposure of personnel working at shipyards under the U.S. Naval Nuclear Propulsion Program (NNPP) and all other Navy sites will now be done with the new TLD system. The model DT-702 technology is a significant improvement relative to the older DT-526 technology, providing more accurate readings, better stability and energy discrimination as well as a lower detection limit.

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PUBLICATIONS

Boukharouba, N., Bateman, F.B., Carlson, A.D., Brient, C.E., Grimes, S.M., Massey, T.N., Haight, R.C., and Carter, D.E., "Measurement of the *n-p* Elastic Scattering Angular Distribution at E_n = 14.9 MeV," Phys. Rev. C **82**, 014001 (2010).

Chantler, C.T., Hudson, L.T., and Best, S.P., "Frontiers in Radiation Physics and Applications: The 11th International Symposium on Radiation Physics," Nucl. Instr. and Meth. A **619** (2010).

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Desrosiers, M.F., and Puhl, J.M., "Absorbed-Dose/Dose-Rate Dependence Studies for the Alanine-EPR Dosimetry System," Radiat. Phys. Chem. **78**, 461-464 (2009).

Desrosiers, M.F., Peters, M., and Puhl, J.M., "A Study of the Alanine Dosimeter Irradiation Temperature Coefficient from 25 °C to 80 °C," Radiat. Phys. Chem. **78**, 465-468 (2009).

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Massillon-JL, G., Minniti, R., Soares, C.G., Maryanski, M.J., and Robertson-K, S., "Characteristics of a New Polymer Gel for High-dose Gradient Dosimetry using a Micro Optical CT Scanner," Appl. Radiat. Isot. **68**, 144-147 (2010).

Mitch, M.G., and Soares, C.G., “Primary Standards for Brachytherapy Sources,” *Clinical Dosimetry Measurements in Radiotherapy,* ed.by, D.W.O. Rogers and J.E. Cygler, Medical Physics Publishing, Madison, Wisconsin, 549-565 (2009).

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Pereira, N.R., Weber, B.V., Apruzese, J.P., Schumer, J.W., Seely, J.F., Szabo, C.I., Boyer, C.N., Mosher, D., Stephanakis, S.J., and Hudson, L.T., “K-line Spectra from Tungsten Heated by an Intense Pulsed Electron Beam,” Rev. Sci. Instrum. **81**, 10E302/1-10E302/7 (2010).

Pibida, L., Minniti, R., and O’Brien, M., “Validation Testing of ANSI/IEEE N42.49 Standard Requirements for Personal Emergency Radiation Detectors,” Health Phys. **98**, 597-602 (2010).

Seely, J.F., and Hudson, L.T., “Laser-Produced MeV Electrons and Hard X-Ray Spectroscopic Diagnostics,” Nucl. Instr. and Meth. A. **619**, 479-486 (2010).

Seely, J.F., Pereira, N.R., Weber, B.V., Schumer, J.W., Apruzese, J.P., Hudson, L.T., Szabo, C.I., and Boyer, C.N., “Spatial Resolution Performance of a Hard X-Ray CCD Detector,” Appl. Opt. **49**, 4372-4378 (2010).

Seely, J.F., Szabo, C.I., Audebert, P., Brambrink, E., Tabakhoff, E., Holland, G.E., Hudson, L.T., Henins, A., Indelicato, P., and Gumberidze, A., “Hard X-Ray Spectroscopy of Inner-Shell K Transitions Generated by MeV Electron Propagation from Intense Picosecond Laser Focal Spots,” High Energy Dens. Phys. **5**, 263-269 (2009).

Seely, J.F., Szabo, C.I., Audebert, P., Brambrink, E., Tabakhoff, E., and Hudson, L.T., “Lateral Propagation of MeV Electrons Generated by Femtosecond Laser Irradiation,” Phys. Plasmas **17**, 023102/1-023102/11 (2010).

Seely, J.F., Szabo, C.I., Feldman, U., Hudson, L.T., Henins, A., Audebert, P., and Brambrink, E., “Hard X-Ray Transmission Crystal Spectrometer at the OMEGA-EP Laser Facility,” Rev. Sci. Instrum. **81**, 10E301/1-10E301/4 (2010).

Sholom, S., Desrosiers, M., Chumak, V., Luckyanov, N., Simon, S., and Bouville, A., “UV Effects in Tooth Enamel and Their Possible Application in EPR Dosimetry With Front Teeth,” Health Phys. **98**, 360-367 (2010).

Smale, L.F., Chantler, C.T., and Hudson, L.T., “The Effects of Cosmic Ray Filtering on Low Intensity X-Ray CCD Data,” Nucl. Instr. and Meth. A **619**, 150-153 (2010).

Soares, C.G., Douysset, G., and Mitch, M.G., “Primary Standards and Dosimetry Protocols for Brachytherapy Sources,” Metrologia **46,** S80- S98 (2009).

Szabo, C., Feldman, U., Seely, J., Curry, J., Hudson, L., and Henins, A., “Asymmetric Cut Crystal Pair as X-Ray Magnifier for Imaging at High Intensity Laser Facilities,” Rev. Sci. Instrum. **81**, 10E311/1-10E311/3 (2010).

Szabo, C., Workman, J., Flippo, K., Feldman, U., Seely, J., Hudson, L., and Henins, A., “Scaling Studies with the Dual Crystal Spectrometer (DCS) at the OMEGA-EP Laser Facility,” Rev. Sci. Instrum. **81**, 10E320/1-10E320/3 (2010).

Invited Talks

Desrosiers, M.F., "Radiation Accidents: How Bones and Teeth are Used to Measure Human Exposures," Wilson College, Chambersburg, Pennsylvania, December 2009.

Desrosiers, M.F., "Physical Methods for Biodosimetry after Radiologic and Nuclear Events," 18th Annual Meeting of the Council on Ionizing Radiation Measurements and Standards (CIRMS), Gaithersburg, Maryland, October 2009.

Dewey, M. Scott, "Fundamental Properties on the Neutron," NIST 2009 Summer School on Fundamental Physics, Gaithersburg, Maryland, June 2009.

Hudson, L.T., "Aviation Security Standardization: X-Ray and Gamma-Ray Standards," 9th Annual Plenary Meeting, ANSI Homeland Security Standards Panel (HSSP), Arlington, Virginia, November 2010.

Hudson, L.T., "X-Ray and Gamma-Ray Standards for Aviation Security," 19th Annual Meeting of the Council on Ionizing Radiation Measurements and Standards (CIRMS), Gaithersburg, Maryland, October 2010.

Hudson, L.T., "Metrology for Portable X-Ray Light Sources," National Bomb Squad Commanders Advisory Board, Rio Grande, Puerto Rico, June 2010.

Hudson, L.T., "National Standards for X-Ray and Gamma-Ray Security Screening Systems for Bulk Explosives Detection," ANSI Homeland Security Standards Panel (ANSI-HSSP) Workshop: Standards for Non-Invasive Inspection Systems for Homeland Security, Gaithersburg, Maryland, April 2010.

Hudson, L.T., "Metrology for Extreme X-Ray Light Sources," 11th Symposium of the International Radiation Physics Society, Melbourne, Australia, September 2009.

Hudson, L.T., "Metrology for Extreme X-Rays," Colloquium for Chinese Academy of Sciences, Beijing, China, August 2009.

Karam, L.R., "Standards for Radiation-Based Medical Imaging: toward harmonization," Federal Laboratory Consortium, Biomedical Technology Forum, Thomas Jefferson National Accelerator Facility, Newport News, Virginia, June 2010.

Karam, L.R., "The CIPM MRA: Implications for SIM Activities in Dosimetry," 5th Brazilian Metrology Congress, Salvador, Brazil, November 2009

Minniti, R., "The Use of Cs-137 Irradiators in the United States for Calibrating Instruments," Panel Member at the Nuclear Regulatory Commission Public Hearing, Bethesda, Maryland, November 2010.

Minniti, R., "Radiation Measurements at NIST in Support of NAVSEA," Annual RADIAC Program Review, Huntsville, Alabama, July 2009.

Minniti, R., (co-authors: Pibida, L.S. and Soares, C.G.), "Measurements of Radiation Detectors Made on a Tissue Equivalent Phantom and Free in Air," 54th Annual Meeting of the Health Physics Society (HPS), Minneapolis, Minnesota, July 2009.

Mitch, M.G., (co-authors: O'Brien, C.M., Tosh, R., Seltzer, S.M., McClelland, M.R. and Eardley, D.F.), "Traceability to National Measurement Standards for Electronic Brachytherapy", 52nd Annual Meeting of the American Association of Physicists in Medicine (AAPM), Philadelphia, Pennsylvania, July 2010.

Mitch, M.G., (co-authors: Tong, L. and Seltzer, S.M.), "Characterization of In-Air Anisotropy of Brachytherapy Sources Using Clinical Ionization Chambers," 51st Annual Meeting of the American Association of Physicists in Medicine (AAPM), Anaheim, CA, July 2009.

Mitch, M.G., (co-author, Soares, C.G.), "Primary Standards for Brachytherapy Sources," 2009 American Association of Physicists in Medicine (AAPM) Summer School, Colorado College, Colorado Springs, Colorado, June 2009.

Mitch, M.G., (co-authors: DeWerd, L.A., Minniti, R. and Williamson, J.F.), "Treatment of Uncertainties in Radiation Dosimetry," 2009 American Association of Physicists in Medicine (AAPM) Summer School, Colorado College, Colorado Springs, Colorado, June 2009.

Mitch, M.G., (co-author, Seltzer, S.M.), "Air Kerma Strength Standards for LDR Brachytherapy," CCRI(I) Brachytherapy Working Group Workshop on Brachytherapy Metrology, BIPM, Sevres, France, May 2009.

Mitch, M. G., (co-author Seltzer, S.M.), "Metrology for I-125, Pd-103, and Cs-131 Seeds," CCRI(I) Brachytherapy Working Group Workshop on Brachytherapy Metrology, BIPM, Sevres, France, May 2009.

O'Brien,C M., "Summary of Section I of the Consultative Committee for Ionizing Radiation (CCRI) (X- and Gamma-Rays, Charged Particles) 19th meeting at the BIPM May 13-15, 2009," Inter-American Metrology System (SIM) meeting, Rio de Janeiro, Brazil, November 2009.

Tosh, R. (co-author, Chen-Mayer, H.), "Status of the NIST Primary Standard Water Calorimeter for Co-60 Beams," 52nd Annual Meeting of the American Association of Physicists in Medicine (AAPM), Philadelphia, Pennsylvania, July 2010.

Scientific and Technical Staff Vitae

BATEMAN, FRED B., NUCLEAR PHYSICS, B.Sc., Physics, Ohio Univ., 86; Ph.D., Nuclear Physics, Ohio Univ., 94; Post-doctoral Research Assoc., Nuclear Physics Group, Ohio Univ., 94-95; Post-doctoral Research Assoc., Neutron and Nuclear Science Group, Los Alamos National Laboratory 95-98; Research Physicist, NIST 98-present. Res: Nuclear technology, radiation processing, industrial and medical dosimetry, accelerator technology, and accelerator operations. Member: American Physical Society, ASTM E10.01. Co-chair: ASTM E10.01,CIRMS, Task Group H.

BERGSTROM, PAUL M., PHYSICS. B.Sc., Electrical Engineering Pennsylvania State Univ., 82; Ph.D., Univ. Pittsburgh, 92; Univ. of Tennessee Post. Doc. Fellow Lawrence Livermore National Lab. Post. Doc. Fellow 94-97, Staff Member 97-00, Physicist, NIST 00-present, Res: Homeland Security applications, Radiation interactions, computational dosimetry, computational atomic physics including the interactions of photons, electrons and positrons with atoms, Monte Carlo Methods including the transport of photons, electrons and positrons.

DESROSIERS, MARC F., PHYSICAL CHEMISTRY. B.Sc., Boston College, 78; Ph.D., Univ California at Santa Barbara, 83; Argon National. Lab. Post. Doc. Fellow, 84-86; Research Assoc. Prof., Univ. of Maryland-Baltimore, County, 86-89;Research Chemist, NIST, 1989-present Res: Radiation interactions (inorganic to biological), electron paramagnetic resonance. Member: ASTM, CIRMS.

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HUDSON, LAWRENCE T., PHYSICS, B.Sc., Mississippi College, 83; M.Sc, Vanderbilt Univ., 86; Ph.D., Vanderbilt Univ., 89; NASA, Johnson Space Center, 79-83; Sandia National. Lab. (summer) 83; Oak Ridge Natl. Lab. (summer) 84; NIST/NRC Post Doc. Fellow, 90-91; Physicist NIST, 90-present. Res: X-ray metrology, spectroscopy, standards and applications. Member: APS CIRMS, Life Member, Executive Council, International Radiation Physics Society. .

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MITCH, MICHAEL G., PHYSICS. BA, Gettysburg College, 88; Ph.D., Penn State Univ., 94; Summer Research Student, Dept. of Phys., Pennsylvania State Univ., 87; Teaching Asst., Dept. of Phys., Pennsylvania State Univ., 88-90; Research Asst., Dept. of Phys., Pennsylvania State Univ., 89-94; Assoc. Research Scholar, Dept. of Materials and Nuclear Engr., Univ. Maryland and NIST, 94-98; Physicist, NIST, 98-10. Leader, Radiation Interactions and Dosimetry Group, 10-present. Res: Brachytherapy source calibration, dosimetry, and x-ray spectrometry. Member: APS, AAPM.CIRMS

O'BRIEN, C. MICHELLE, PHYSICS. AS, Chattanooga State, 88; B.Sc, Univ. Tennessee, Knoxville, 90; M.Sc, Univ. Tennessee, Knoxville, 93; Health Physics Tech., Brookhaven National Lab., Summers of 88/89; U.S. Peace Corps, Benin, West Africa, 90; Research Asst., ORNL, 91-93; Physicist, NIST 93-present. Res: Instrument calibration, characterization of x-ray calibration mammography range. Member: HPS, CIRMS.

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TOSH, RONALD E., PHYSICS, BA, Kenyon College, 84; Ph.D., Univ. Pittsburgh, 92; Univ. of Delaware Post-doc. Fellow, 92-97; Applications Engineer, National Instruments, 97-98; Field Sales Engineer, National Instruments, 98-04; Physicist, NIST, 04-present. Res: development of primary photon and electron dosimetry standards, non-invasive temperature measurements, laboratory automation. Member: CIRMS, International Radiation Physics Society.

WALIA, JASON S., HEALTH PHYSICS, B.Sc, James Madison Univ., 04; M.Sc, Georgetown Univ., 09; Physicist, NIST, 09-present. Res: Brachytherapy seed measurements and beta source measurements. Member: HPS, ANS..

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Caswell, Randall	Self	Radiation transport calculations

Radiation Interactions and Dosimetry Group

Al-Sheikhly, Mohamad	Univ. of Maryland College Park, MD	High dose measurement techniques
Berger, Harold	Digitome Co. Davidson, NC	X- ray tomosynthesis, variable depth laminography
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Domen, Stephen	Self	Water Calorimetry
Dryden, John W.	Digitome, Co. Davidson, NC	Volumetric x-ray imaging
Glover, Jack L.	Univ. of Melbourne Victoria, Australia	National image quality standards
Kato, Masahiro	NIAI of Science & Technology Ibaraki, Japan	Standard of absorbed dose to water
Kinnane, Mark N.	Univ. of Melbourne Victoria, Australia	Precision metrology of absolute x-ray wave lengths
Morehouse, Kim	Food and Drug Administration Rockville, MD	Study of possible radiolytic products in food
Motz, Joseph W.	Self	X- ray tube wing cathode-anode
Pagonis, Basile	Western Maryland College Westminster, MD	Thermoluminescence Dosimetry Meas. & Brachytherapy Sources
Picard, Susanne	Bureau International des Poids et Mesures Sèvres Cedex, France	BIPM primary-standard calorimeter

Robertson, Scott P.	Univ. of Maryland College Park, MD	BANG-3 pro gels
Roger, Philippe M.	Bureau International des Poids et Mesures Sèvres Cedex, France	BIPM primary-standard calorimeter
Romanyukha, Alexander	U.S. Naval Dosimetry Center Bethesda, MD	NVLAP category exposures
Selwyn, Reed G.	Naval Dosimetry Center Bethesda, MD	NVLAP category exposures
Seltzer, Stephen M.	Self	Radiation transport calculations & analysis
Soares, Christopher G.	Self	Photon & beta particle sources
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Steel, James S.	Rayex Corp Gaithersburg, MD	Power enhancement of x-ray tubes

IONIZING RADIATION DIVISION (682)

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