Recent Dosimetry Activities at the NIST

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1. INTRODUCTION

The following is intended as a general overview of activities by the Radiation Interaction and Dosimetry Group, Ionizing Radiation Division, National Institute of Standards and Technology (NIST), USA, for the meeting of Section I (X and γ rays, electrons) of the Consultative Committee on Ionizing Radiation (CCRI), May 14-16, 2007, Paris. The material was taken from information gathered for NIST program reviews, and covers roughly calendar years 2005 and 2006. Our technical activities are summarized in Section 2, identifying staff members involved in each project; Section 3 lists the Group's publications for the period.

I'm sad to report that John Hubbell died on March 31, 2007, six weeks after suffering a massive stroke. John was the leader for more than 40 years in the critical evaluation of photon interaction cross sections. Although retired from the Radiation Theory Section of the National Bureau of Standards (now NIST), he continued as a guest researcher in the Radiation Interactions and Dosimetry Group until his stroke. John was honored for his work by organizations too numerous to list here, and he was a founder of the International Radiation Physics Society. He was long a colleague and friend, both to me and to very many in radiation physics; he will be missed.

2. TECHNICAL ACTIVITIES

A. THEORETICAL DOSIMETRY

New Evaluations of the Compton Cross Section for Photon Interaction with Atoms. Computations have been completed toward creating a new NIST database for inelastic photon-atom scattering. This database provides total cross section and subshell ratios for the ionization or Compton component of inelastic photon-atom scattering. Additionally, mass-energy absorption and mass-energy transfer coefficients are provided. These data are provided for all elements with nuclear charge *Z* from 1 to 92 and for energies from 1 keV to 20 MeV, the region where this process is most significant in the attenuation of photons. The computations were performed in the relativistic impulse approximation, which provides the cross section doubly differential in scattered photon energy and angle on a subshell-by-subshell basis. This cross section was computed using Dirac-Fock momentum distributions for the individual subshells. These results were then numerically integrated over energy and angle to obtain the totals. In the case of the mass-energy absorption and energy-transfer coefficients, additional data was required relating to emission of relaxation photons and bremsstrahlung radiation by ejected electrons. These data were taken from the Lawrence Livermore National Laboratory Evaluated Atomic Data Library and the NIST database corresponding to ICRU Report 37. In addition to this database, based on part of the photon-atom interaction, the resonant Raman-Compton term has now been integrated to provide additional, small contributions to the overall cross section. (P.M. Bergstrom)

Review of Information on Photon-Interaction Cross Sections. Periodically the Photon and Charged-Particle Data Center reviews progress on the development of radiation-interaction data to assess the need for new or updated standard-reference databases. Such a review is being carried out of the available theoretical and measured data on elastic (Rayliegh or coherent) scattering of photons and of the available measured data on the attenuation coefficients for photons in elemental materials. The focus is on recent advances that could improve the accuracy of photon-interaction data tabulations by the NIST and others, and includes a quantitative assessment of the impact of new data, particularly from S-matrix calculations, on possible new NIST compilations of photon attenuation coefficients. (J.H. Hubbell)

Computational Radiation Physics. Efforts in this area have been directed towards updating Monte Carlo resources and towards beginning to apply those resources to modeling the radiation sources utilized by the Radiation Interactions and Dosimetry Group. In particular, updated versions of the MCNP, PENELOPE and EGS codes have been acquired, installed and maintained. The EGSnrc code and the corresponding BEAM code were utilized to generate phase-space files for the output of the Clinac 2100C accelerator at both photon beam energies (6 MV and 18MV). Preliminary comparisons with measurements have taken place. We expect to a complete computational model of this source which will be used in theoretical dosimetry applications. Additionally, work has begun to model the NIST's lower-energy x-ray sources. Other applications in computational radiation physics include simulations to support homeland-security applications, to characterize source emissions, to determine detector responses to radiation, to determine spatial distributions of absorbed dose, and to generate results for operational quantities used in radiation protection. (P.M. Bergstrom)

B. Quantum Metrology

X-Ray Spectroscopy. The NIST-NRL HENEX instrument, a suite of curved-crystal spectrometers for the National Ignition Facility, was upgraded, tested and calibrated with a micro-focus Mo x-ray source at the NIST Advanced Metrology Laboratory and the 420 kV set in the Radiation Physics Bldg. A study related to reducing background due to crystal-fluorescence and high-energy x-ray scattering led to a publication on operation of such instruments in high-energy-density environments such as magnetic- and inertial-confinement fusion facilities. The plate functions were calibrated in vacuum from 1 keV to 20 keV using a custom broadband vacuum calibration facility. Finally, the instrument was deployed at the largest laser in the world (at U. Rochester) during the week of May 23. The results are being published in Radiation Physics and Chemistry. This instrument has now been demonstrated to be an effective diagnostic of plasma temperature as well as laser and target performance, providing unique and pioneering x-ray diagnostic capabilities in high-energy-density environments such as megajoule-class ICF facilities.

In a related effort, we designed a new dual-crystal spectrometer to measure high-Z, K-shell spectra (e.g., Au $K\alpha$) at laser-produced plasma sources. The spectrometer was constructed at NRL, tested at the NIST, and fielded at the Omega laser during August 8 to 12. Gold L-shell spectra were obtained, as were high-energy continuum spectra, but these particular shots were not energetic enough to produce K-shell vacancies. This work is of great interest in the high-energy-density environment of the National Ignition Facility as they make use of gold hohlraums in their indirect-drive fusion program. (L.T. Hudson).

Low-Energy Absolute X-Ray Wavelength Metrology. A vacuum double crystal spectrometer (VDCS) is being used to set world records in absolute x-ray wavelength determination (at 1 ppm and tied to the definition of the meter) from 1 keV to 12 keV. In support of the NIST's commitment to core competence in metrology, this instrument has moved to the Advanced Measurement Laboratory to a custom-designed environment with extreme temperature and vibration stability. This instrument performs precision x-ray wavelength measurements in support of high-accuracy transfer standards needed in fundamental experiments at the NIST and around the world. In many cases, the error budget of such experiments is limited by the CRC (Bearden) wavelength tables. The results will also complement the NIST's new x-ray wavelength tables project by making modern measurements of transition energies that differ significantly from the most recent theoretical calculations. A novel (optical polygon/homemade nulling electronic autocollimator) calibration technique of the angle encoder has been proven at the 0.04 arc second level and the upgraded instrument is now able to perform *in situ* alignment of the x-ray crystal optics. In addition to wavelength metrology, the VDCS will also perform the first direct measurements of the index of refraction in silicon using an innovative approach. (L.T. Hudson, M. Kinnane)

Applications of Diagnostic X-Ray Spectrometers. We continue to design, produce, and calibrate bent-crystal diagnostic spectrometers for customers around the world. These have or are scheduled to characterize the performance and x-ray spectra from 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. In FY06, the NIST in collaboration with NRL has assembled and fielded a two-channel crystal spectrometer in Cauchois geometry to characterize the emissions from low- and high-Z planar foils irradiated by intense picosecond and femtosecond laser pulses from the TITAN laser facility at Lawrence Livermore National Laboratory. In a single-hit regime, spectra were registered from a sequence of elements from Mo to Au, spanning the x-ray energy range from 17 keV to 69 keV. The development of such exotic x-ray sources is motivated by the interest in performing radiography of imploding inertial confinement fusion cores using Compton scattering to observe cold, dense plasma. This works supports the development of high-energy K-alpha x-ray backlighters for such radiography experiments at the National Ignition Facility. (L.T. Hudson)

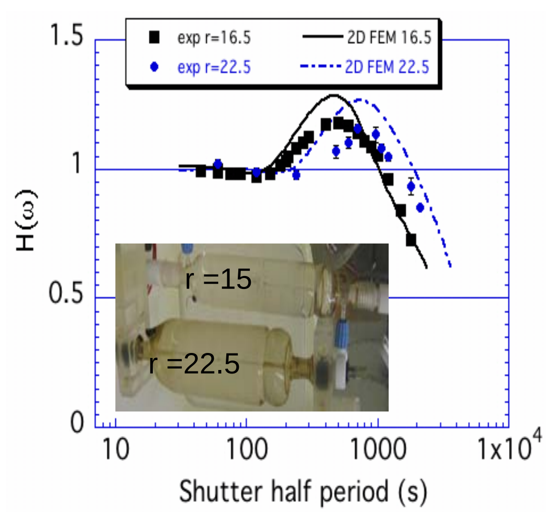
C. MEDICAL DOSIMETRY

Advances in Water Calorimetry. A decade ago, Steve Domen developed a sealed-water calorimeter at the NIST that was used to make the first determination of the absorbed dose at a point in water from ^{60}Co gamma-ray beams. This result has served as the NIST standard, and has been disseminated through the Accredited Dosimetry Calibration Laboratories (ADCLs) to the medical physics community. Since then, the adoption by the medical physics community of dosimetry protocols based on absorbed dose to water, rather than air kerma, has driven development of newer calorimeter designs incorporating modern technologies, such as lock-in detection and computer control, as well as alternative technologies for sensing temperature, such as ultrasound.

Automated control of the calorimeter measurements has helped us to explore wide ranges of exposure time and absorbed dose for purposes of studying the calorimeter response and improving signal-to-noise. For radiotherapy-level beams, dose rates are small, inducing temperature changes in the microKelvin range over a typical experimental run. These small signals are susceptible to artifacts due to heat conduction and convective movement of the water. Traditional approaches to mitigating these problems involve limiting the exposure times, spacing out measurement runs in order to allow thermal equilibration within the water, and using external refrigeration systems to keep the water temperature near 4 ^{o}C (effectively shutting off convection). Finite-element calculations then are used to estimate the remaining conduction artifacts.

In an effort to reduce some of these restrictions on experimental method and to leverage the capabilities of computer automation for repetitive measurements, we have been developing an approach to collecting and analyzing experimental data that emphasizes spectral characteristics of both signal and heat-transfer artifacts. Accordingly, physical processes like conduction and convection are expressed as transfer functions that operate on the input radiation signal to produce a heating output signal that is attenuated and phase-shifted in the frequency domain. This approach is a parallel but more sensitive characterization of the distortion due to the artifacts in the time domain.

Shown on the right are recent results on transfer functions obtained experimentally (solid dots) from two detector vessels of a different diameter. In a stirred system such as ours, the transfer function has a maximum at a particular shutter period, which depends on the vessel diameter. Finite element simulations (shown as lines in figure) verified this shift of the maximum toward a lower period for a smaller diameter, qualitatively. The deviation from unity is then the frequency-dependent correction factor for heat conduction for the



corresponding vessel. Some refinements of this work are needed to correlate our approach with the conventional correction factors derived from time-domain signals, which depend on exposure time and specifics of the equilibration intervals that vary from experiment to experiment. Ultimately, our approach should enable the determination of conduction correction factors for arbitrary choice of these timing parameters and thereby facilitate certain comparisons between results issued by different laboratories.

Application of these spectral methods to convection artifacts could be problematic because of nonlinearities in the equations of motion. However, because the dose rates are quite low, the induced thermal inversions, hence the nonlinearities, might be amenable to a perturbative treatment. Our preliminary investigations with the calorimeter and finite-element modeling suggest that this is indeed the case. Paralleling earlier experiments by Domen on convection induced by self-heating in thermistors, we are using the thermistors in the calorimeter to study the spectral signature of stable convection due to ohmic heating. We expect to expand this point-source study to address possible convection induced by dose gradients at the beam penumbra and near the surfaces of non-water elements in the phantom, which produce significant systematic errors in dose estimates from water calorimeters. (H.H. Chen-Mayer, R.E. Tosh).

Possible 3-D Absorbed-Dose Profiling in Water. In conjunction with our water-calorimetry research, we are working with Luna Technologies of Hampton, VA. With the successful completion of their Phase I SBIR grant, we will evaluate ultrasonic techniques for measuring radiation-induced temperature changes in water, which may thereby result in a new type of water calorimeter. With the award of Phase II funding this year, the Group expects to receive a research prototype ultrasonic sensor system that uses pulsed phase-locked loop (PPLL) technology to derive temperature measurements in a water phantom with better than 10 μK resolution. Should these investigations prove to be promising, efforts will be directed toward developing an ultrasonic tomographic system based on digital PPLL technology that would provide rapid 3-dimensional absorbed-dose profiles in water and, possibly, other media. (H.H. Chen-Mayer, R.E. Tosh).

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. More than 700 seeds of 33 different designs from 18 manufacturers have been calibrated using the WAFAC since 1999.

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. The Seltzer-Mitch chamber is an ionization chamber that was designed and built at the NIST specifically to achieve greater efficiency than currently possible with commercially available chambers in prostate brachytherapy seed characterization.

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.

To verify that seeds of a given design calibrated at the NIST are representative of the majority of those calibrated in the past, 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.

Such complete characterization of a seed is necessary for quality assurance of WAFAC measurements, and to maintain accuracy in the transfer of standards to secondary calibration laboratories. Anisotropy measurements, along with spectrum dependence in well-chamber response data, have been used to determine a reasonable tolerance criterion for acceptable variability in well-chamber calibration coefficients for a given seed design, and thus in a secondary air-kerma-strength standard established using well chambers. Data from two Accredited Dosimetry Calibration Laboratories (ADCLs) and the seed manufacturer, in addition to the results of the NIST measurements, are compiled and checked as a function of time to ensure the continuous validity of the calibration traceability chain from the NIST to the ADCLs and manufacturers. (M.G. Mitch)

Evaluation of Uncertainty in Low-Energy Photon Brachytherapy Dosimetry. The NIST is participating in the newly formed 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 for identifying most all sources of uncertainty towards quantifying realistic clinical evaluation of treatments. The NIST is in a unique position to contribute to this effort by analyzing ionization chamber, 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. (M.G. Mitch)

Calibrations of a Miniature X-Ray Source Used for Electronic Brachytherapy. In a collaborative effort with the University of Wisconsin, experimental measurements of the air-kerma rate from a miniature x-ray source were performed using two existing NIST x-ray standards. The Xoft AXXENT™ source was designed to provide low-energy x-rays (< 50 keV) for use in brachytherapy. Air-kerma rates from several of these sources were measured using the NIST Attix and Ritz free-air ionization chambers that are the U.S. national standards for such beams. The Xoft sources were operated at 50 kV with a beam current of 100 μA. The possibility of transferring the air-kerma calibration to a well-type ionization chamber was also investigated, as well chambers will be employed as an on-site secondary standard in therapy clinics to verify source output prior to treatment. Further work will be necessary to identify more robust measurements with the primary x-ray standards for this application and to fully develop the transfer of air kerma to the well chamber for these sources. (C.M. O'Brien, M.G. Mitch, S.M. Seltzer)

Absorbed-Dose-Rate Measurements of Low-Energy-Photon Brachytherapy Sources. Measurements of low-energy photon emitting brachytherapy sources are being performed at the NIST using small-volume ionization chambers, micro-scintillators, radiochromic film and thin thermoluminescence dosimeters (TLDs). These measurements are being performed in a specially designed water phantom with the detectors either in water or covered with minimal layers of water-equivalent plastic. Absorbed dose rate measurements of a 50 kV x-ray probe continued in collaboration with McDaniels College students and faculty. In addition, measurements were continued of a novel ophthalmic applicator which employs high activity, annular ^{103}Pd source for the treatment of age-related macular degeneration. There are difficulties with these latter measurements due to the low energies involved (20 keV), probably related to interface effects between the detectors and their holders or housings. These problems are under investigation. (C.G. Soares)

Methods to Calibrate and Characterize Ophthalmic Applicators for the Treatment of Age-Related Macular Degeneration. We currently work with two manufacturers who are testing sources for treating age-related macular degeneration. Macular degeneration is the leading cause of severe irreversible blindness in the US. Theragenics Corporation of Buford, GA is using an annular source of ^{103}Pd (with an activity of a few Ci), which is placed behind the eye to deliver 20 Gy to the retina at a depth of 3 mm. Another manufacturer is testing a source with a different geometry and isotope, which information must remain proprietary at present. For these measurements, an automated water phantom and various small-volume detectors are used to work towards the goal of developing an absorbed-dose standard for photon brachytherapy sources. Essential to such a standard is the measurement of the absorbed-dose rate in water or water-equivalent media. (C.G. Soares)

Beta-Particle Emitting Ophthalmic Applicator Calibration Service. The NIST primary standard for beta-particle brachytherapy sources relies on extrapolation-chamber measurements, but quoted uncertainties are unacceptably high (>10 % at 2σ), mainly because of curvature of the current *vs*. air-gap function, which leads to uncertainty in the measured absorbed-dose rate. Recent calculations have shown that this curvature can largely be removed through the application of a divergence correction to account for ionization losses at finite air gaps associated with the geometry of the source and extrapolation chamber. The divergence corrections were calculated using various Monte Carlo codes; most of the calculations used to determine the correction were done with EGSnrc Version 3. Air gaps between 0.01 mm and 0.5 mm were modeled, as well as three collecting-electrode materials: carbon, water, and D400 conducting plastic.

Collecting-electrode diameters between 1 mm and 8 mm were modeled, and for each of these collecting-electrode/air-gap combinations three ^{90}Sr/Y beta-particle source geometries were modeled: a 1 cm diameter ophthalmic applicator, and 0.56 mm and 2.3 mm diameter seeds placed at a depth of 2 mm in water. The corrections are now being applied to all measurements since 1 January 2003. They are also being applied to prior measurements to assess the changes associated with the curvature in the current vs. air-gap function. An additional outcome of these investigations is a revised value for the electrode backscatter correction. Initial findings indicate the use of the new corrections will result in dose rates of ophthalmic applicators being increased by approximately 6.5 %. As a result of these calculations, the NIST uncertainty budget for these calibrations has been revised, and the expanded (k = 2) uncertainty has been lowered from 12 % to 7 %. (C.G. Soares)

X-Ray Calibration Range Measurements. The calibration and irradiation of instruments that measure x-rays are performed in the NIST x-ray calibration facilities in terms of the physical quantity air-kerma. Calibrations are performed by comparing the instrument to a NIST primary standard, which include four free-air chambers. Air-kerma-measurement comparisons with the BIPM and other primary standards laboratories are conducted for quality assurance. Three comparisons have recently been concluded. The first compared the NIST and the BIPM standards for air kerma in medium-energy x-rays. The comparison involved a series of measurements at the BIPM and the NIST using the air-kerma standards and three NIST reference-class transfer ionization chamber standards. Reference beam qualities in the range from 100 kV to 250 kV were used. The results show the standards to be in reasonable (between -0.1 % and 0.7 %) agreement within the combined standard uncertainty of the comparison of 0.48 %. Trends with radiation quality will now be investigated to evaluate differences. A report of the comparison will soon be available.

The second comparison was the first involvement for the NIST in a EUROMET comparison for x-ray standards. The stated objective, according to the test protocol for the EUROMET Project 545 is to extend the mutual traceability among the air-kerma standards of NMIs to ISO 4037 narrow-spectrum-series radiation qualities. The project is intended for NMIs that have participated in recent BIPM key comparisons of their primary standards for BIPM radiation qualities. The ISO narrow-spectrum series of reference radiation qualities have been maintained at the NIST since the late 1990s. Three various-sized transfer standards, maintained by the PTB in Germany, were sent to each of the eleven participating NMIs. This comparison was conducted using two of the NIST primary air-kerma standards in two of the x-ray ranges. The test compares the dosimetric procedures at levels lower than those for therapy and investigates the influences of larger field sizes. The CCRI(I) endorsed project 545 was endorsed and encouraged participation of laboratories from outside the EUROMET area.

The third comparison began in 2006, and involved a series of measurements at the PTB and at the NIST using the air-kerma standards and two NIST reference-class transfer ionization chamber standards. Tungsten and molybdenum reference beam qualities in the range from 10 kV to 50 kV were used. The initial measurements were conducted at the NIST in January and at the PTB in March of 2006. The final measurements will be completed at the NIST in 2007, with a formal report to follow. This indirect comparison with the PTB will be the third comparison for mammography energies, but the first for the NIST using the recently developed BIPM/CCRI reference beam qualities. The results of the CCRI beam comparison will verify the new correction factors implemented for those techniques for the NIST standard, prior to the next direct BIPM comparison.

In addition to participating in measurement comparisons, the NIST x-ray facilities are used to conduct proficiency tests for various NIST customers. The NIST customers, which include secondary-calibration facilities, chamber manufacturers, nuclear industry, Department of Energy, Department of Defense, private calibration facilities, medical facilities and the Food and Drug Administration, request calibrations in terms of Gy/C for various reference-quality ionization chambers to achieve traceability to the NIST. Recent updates have been made to our website explaining the proficiency test policy (see http://physics.nist.gov/Divisions/Div846/Gp2/gp2.html).

Corrosive chilled water, used to cool our x-ray tubes, damaged a heat exchanger and resulted in the failure of the 320 kV x-ray system. The replacement of the 320 kV x-ray tube required the re-characterization and verification of the reference beam qualities. The beam uniformity was reestablished at various distances. Two voltage dividers were used to verify and recalibrate the operating voltages on both tungsten x-ray units. No changes were required to the filtration of the beam qualities, resulting in unchanged HVLs. A new chilled-water system will be implemented in the near future. (C.M. O'Brien)

X-Ray Standards. A new free-air ionization chamber has been designed to replace the Wyckoff-Attix chamber, which has been used at the 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 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 the direct measurement of the air-attenuation correction. The plans are complete for the new primary standard, and construction is planned to begin in 2007. Once the new standard is constructed it will be fully evaluated in a parallel measurement arrangement until the correction factors are established and tested. (C.M. O'Brien)

Spectrometry of X-Ray Beam Calibration Ranges Spectrometry measurements of the x-ray beams used in the NIST calibration ranges was initiated in 2006 using a high-resolution HPGe detector, both in the direct beam and at 90° using Compton-scatter spectrometry. Pulse-height distributions were obtained for all the NIST and ISO beams produced by the NIST 100 kV and 300 kV x-ray generators, and are now in the process of being unfolded. (C.G. Soares, C.M. O'Brien, S.M. Seltzer)

National and International Harmonization of Standards for the Air Kerma from ^{60}Co Gamma-Ray Beams. In July 2003 the re-characterization of the NIST therapy-level ^{60}Co vertical beam facility was completed resulting in a newly revised US standard for the air kerma from such beams. Since then the US primary standard has been disseminated to secondary laboratories throughout the US via calibration of ion chambers. Excellent agreement, to within less than 0.20 %, between the NIST and each of the AAPM Accredited Dosimetry Calibration Laboratories (ADCLs) was achieved as demonstrated by transfer measurements and proficiency tests.

During the spring of 2006 a bilateral international comparison of national measurement standards for air kerma from ^{60}Co therapy-level beams was initiated between the PTB and the NIST. This is the first international comparison performed since the implementation of the new US standards of July 1, 2003. Excellent agreement was obtained between the two laboratories, to within less than 0.20 %.

A new safety interlock system has been designed and the installation has been completed during the spring of 2006. The improvement provides additional safety indicators and a control system to prevent the inadvertent entrance of a user. In addition, an upgrade and improvement of the compressed-air lines used for controlling the shutter mechanisms of the radioactive sources was performed. The new system has been in operation since June 2006 and is in compliance with new NRC regulations. (R. Minniti)

Improvements to Accelerator Facilities. The Radiation Interactions and Dosimetry group continues to support research efforts in industrial and medical dosimetry, homeland security, and radiation-hardness and materials-effects studies.

This past year saw continued development of the Clinac 2100C medical accelerator facility. Using a recently acquired radiation scanner, depth-dose measurements in water were conducted in order to validate machine performance. The response of the Clinac's internal dose monitors was checked against a NIST-calibrated ionization chamber, following the method prescribed by the manufacturer and using the AAPM TG-51 protocol for the measurement of absorbed dose. Software controls have been implemented to allow the beam to be cycled on and off for a fixed period of time and a preset number of cycles. This technique will allow frequency-domain analysis of the response of a second-generation Domen-type water calorimeter. NIST personnel recently used the Clinac accelerator to evaluate the performance of a second-generation Domen-type water calorimeter by comparing its response to that of a NIST-calibrated ionization chamber. This comparison showed quite good agreement amongst the two devices and gives us confidence in the performance of the accelerator and in the dosimetry methods used. The water calorimeter will become the primary national standard for high-energy absorbed dose to water. Plans are to make use of the Clinac in a high-energy x-ray calibration laboratory to be based on this primary dosimetry standard.

A number of facility improvements and upgrades are underway on the MIRF and Van de Graaff accelerators. These include replacement of the Van de Graaff accelerator tube, refurbishment of the electron source, and installation of new resistors in the high-voltage resistor chain. This will result in improved voltage stability and much higher beam intensities. On the MIRF accelerator, new high-power RF windows and high-voltage arc detectors are being installed on the RF waveguide. These should lead to improved system performance, prolonged equipment life and less down time for repairs. (F.B. Bateman, M.R. McClelland, D.F. Eardley)

D. Protection and Accident Dosimetry

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 for several years. The measurement system is automated, and capable of measuring extremely low absorbed-dose rates. The automation-control software has been rewritten in LabVIEW code. The second-generation beta-particle secondary standard system (BSS2), which includes the isotope ^{85}Kr, is now 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 the NIST, allowing a direct intercomparison of calibrations. The systems are also being used for the dosimetry characterization of a photo-stimulable luminescence phosphor imaging system. The standardized techniques developed at the PTB and the NIST are now included in an International Organization for Standardization draft standard and are being implemented in the NIST calibration service. The calibration service has been thoroughly re-documented for inclusion in the Division Quality Manual. The NIST participated successfully in a EUROMET supplementary comparison of absorbed-dose rate in tissue for beta radiation. (C.G. Soares)

Upgrades of Gamma-Ray Calibration Facilities. The Radiation Interactions and Dosimetry Group of the Ionizing Radiation Division maintains and disseminates the national measurement standards for air-kerma (exposure) from ^{60}Co and ^{137}Cs gamma-ray beams. The dissemination of the primary standard is performed via calibration of gamma-ray measuring instruments using one of 7 NIST gamma-ray sources. These calibration facilities provide a broad range of air-kerma rates: two ^{137}Cs sources provide air-kerma rates from 4.5 mGy/h to 100mGy/h; a third ^{137}Cs source provides air-kerma rates of 2.1 Gy/h and 3.3 Gy/h; two ^{60}Co sources provide air-kerma rates from 0.2 mGy/h to 3.0 mGy/h; and two ^{60}Co teletherapy-level sources provide higher rates of 58 Gy/h and 15 Gy/h. The NIST standards are disseminated routinely through a number of US secondary standard-instrument calibration laboratories that include the US Navy, US Army, US DoE, state laboratories, and instrument manufacturers. A number of upgrades have been performed, which include new compressed-air lines for actuating the shutter systems in four of these radiators. A new shutter controller and interlock system has been build and tested for the lower-level ^{60}Co irradiator. The new system performs the functions of the older system and provides additional shutter-timing information that will be used for monitoring the stability of the calibration system over time. Plans are to develop data-acquisition software and integrate the new system for the use of instrument calibration.

The upgrade of the ^{137}Cs irradiator used in the newly developed low-level calibration range includes an improved positioning system for the five ^{137}Cs sources in the irradiator. The range is used for NIST-traceable calibrations of ionization chambers and other gamma-ray detection instruments at very low air-kerma rates, down to ≈3 μGy/hr, approaching environmental-dosimetry levels. The new range consists of a ^{137}Cs irradiation source and an instrument-positioning system. Ionization chambers, as well as gamma-ray detection instruments, can be positioned precisely over distances from 60 cm to 450 cm. Data-acquisition software has been developed to interface with an electrometer, a pressure transducer, and a temperature meter. A final re-characterization of the air-kerma rates delivered by this improved system is underway. (R. Minniti)

Large Chambers Used for the Standardization of ^{137}Cs Gamma-Ray Beams. Large-volume ionization chambers with significantly different physical properties were used for measuring air-kerma rates (approaching environmental levels) from ^{137}Cs gamma-ray beams. The chambers are of two types: pressurized or open to the atmosphere. The walls of the pressurized chambers are made of stainless steel in order to contain the pressurized gas. The chambers that are open to the atmosphere have air-equivalent plastic walls. As a result of their different construction, the energy response of these chambers is very different over a photon energy range between 30 keV and 662 keV. Measurement results show that, despite the different energy response for the different types of chambers, a very good agreement – at the 0.5 % level – can be expected between chambers. This result is relevant to facilities that need to standardize gamma-ray beams for the calibration of radiation-detection instruments. (R. Minniti)

Gamma-Ray Irradiation of TLDs in Support of the Navy Quality-Assurance Program. For the past several years the NIST has provided radiation measurements in support of the Navy quality-assurance program for testing thermoluminescent dosimeter (TLD) systems. The TLD model DT-526 is a calcium fluoride, solid-state dosimeter that has been used by the Navy since 1973 for monitoring the exposure of personnel working at naval shipyards under the US Naval Nuclear Propulsion Program (NNPP). In support of this program, the NIST provides monthly irradiations of TLDs that are later used to test TLD readers located at the various sites associated with the NNPP. The participants involved in this test include the Space and Naval Warfare Systems Center in Charleston, South Carolina, the Naval Surface Warfare Center in West Bethesda, Maryland, and nearly 100 naval sites, including boats at shipyards, and NNPP locations.

The monitoring of radiation exposure for navy personnel not associated with the NNPP is provided by the Naval Dosimetry Center (NDC) in Bethesda, Maryland. Recently the NIST has assisted NDC with measurements to support the implementation of a new quality-assurance program for testing a newer TLD system based on model DT-702 TLDs for personnel monitoring. Compared to the older DT-526 technology, DT-702 TLDs provide more accurate readings, better stability and energy discrimination, and a lower detection limit. (R. Minniti)

Uncertainties in Organ Absorbed Dose from External Radiation Exposure. The National Council on Radiation Protection and Measurements is preparing a set of reports to outline methods used to assess the uncertainty of the absorbed dose to human organs from exposure to ionizing radiation. This work is intended to address the needs of agencies administering compensation programs for certain exposed populations and to provide for a more scientifically sound assessment of organ-dose uncertainty for use in epidemiological studies of radiation dose and risk (mainly excess cancer induction). This work includes the elucidation of the uncertainties, historical and current, associated with primary measurement standards, personal and area dosimetry radiation-protection measurements, and the conversion to absorbed dose in specific organs. Original contributions have been made through a quantitative investigation on the differences in organ doses to individuals of various sizes, made possible by the increasing availability of Monte Carlo results for realistic voxel phantoms (from imaging data for actual individuals), rather than the usual reference phantoms used in radiation protection. These studies show positive correlations of organ doses with body-mass index, which could potentially be used to reduce the uncertainty in the absorbed dose accumulated over the times of irradiation. (S.M. Seltzer, C.G. Soares)

E. INDUSTRIAL DOSIMETRY

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. This temperature coefficient is 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 where dosimeter temperatures can approach 80 °C. However, the temperature coefficients determined for commercial dosimeters have only been characterized up to ≈50 °C. A comprehensive study of film and pellet dosimeter temperature coefficients has been initiated. Preliminary data revealed modest (0.5 % – 1.0 %) deviations from the predicted value at temperatures above 70 °C. After adjustments and tests were made to the irradiation geometry, the improved measurement precision revealed that the alanine pellet response actually plateaus at 70 °C. Similar revisions to the alanine film experimental design are planned. (M.F. Desrosiers, M. Peters, J.M. Puhl, S.L. Cooper)

Temperature Corrections and Estimating Uncertainties for Industrial Irradiation Processing Dosimetry. Since dosimeter response is affected by the average temperature of the dosimeter during irradiation, the accuracy of this adjustment impacts the quality 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. This temperature coefficient is typically expressed in percent change per degree. The temperature rise in dosimeters irradiated with high-intensity ionizing radiation sources can be appreciable; however, the temperature during irradiation is often difficult or impractical to be measured directly. In the absence of a direct measurement, an estimation of the irradiation temperature is often employed to make this correction for the computation of absorbed dose. Since this aspect of routine dosimetry is difficult to assess in an industrial setting, a study simulating those conditions was undertaken to determine the quality of these data manipulations and estimate the associated uncertainties. Industrial temperature profiles were obtained from industry contacts and simulated in the NIST Gammacells. Typical temperature correction methods used by industry operators were employed and compared to the actual temperature corrections made under controlled conditions at the NIST. Specific recommendations will be detailed in a forthcoming publication with regard to the best methods for computing the average irradiation temperature and to assess the magnitude of the uncertainties associated with the correction. (M.F. Desrosiers, T. Ostapenko, J.M. Puhl)

A Study of Dosimeters Subjected to Prolonged Periods of Storage at Elevated Temperatures Immediately Following Irradiation. A common practice in electron beam dosimetry is to calibrate the dosimeters in situ. This is accomplished by placing routine dosimeters and reference in a phantom with a graphite calorimeter. In this way, dosimeters with rate or radiation energy/quality dependencies can be calibrated under industrial conditions. However, sometimes these dosimeters are not retrieved from the phantom for up to several hours; the temperature of the phantom can remain high, ≈40 °C to 50 °C, during this period. One concern is that the response read from these dosimeters would be different from the response read if they were immediately retrieved from the phantom. A first effort to explore any potential effects measured dosimeters stored at 45 °C for up to 24 hours post-irradiation and found no effect. Additional experiments will be undertaken. (M.F. Desrosiers, S.L. Cooper, J.M. Puhl)

Low-Energy Electron-Beam Dosimetry. Over the past several years, industrial users of low-energy electron beams (LEEB) in the range 80 kV to 125 kV have expressed an increased interest in establishing traceability to national standards. Until recently there was no possibility to calibrate dosimeters or electron beams at these energies. Furthermore, a dosimeter as thin as possible (approaching 10 microns) is preferred. RISØ National Laboratory has been developing a graphite calorimeter for LEEBs over the past few years. In parallel, the NIST has been working with Bruker Biospin and Kodak to develop a thin-film alanine dosimeter. Some of these prototype thin-film dosimeters (the thinnest being 43 microns) were sent to the RISØ to be calibrated at 81 kV, 101 kV and 122 kV. These dosimeters were returned to the NIST and response comparisons were made between these dosimeters and gamma-ray irradiated sets. It was determined that improvements to the RISO calibration and associated uncertainties were needed.

The NIST continues to work with various industry users on related projects. One of these is a study of the B3 radiochromic-film dosimetry system. The initial experiments have included a comprehensive set of tests to characterize the effects of dose and irradiation temperature. A ^{60}Co gamma source was used for these fundamental studies due to the superior accuracy and precision of the dose and temperature/dose control. During the course of this study, it was realized that a greater examination of the post-irradiation thermal annealing step would be necessary. Since B3 film deformation is a known consequence of exposure to elevated temperatures, a photographic record of the films was made. (M.F. Desrosiers, T. Ostapenko, J.M. Puhl)

Internet-Based Calibration Services. Several years ago, the NIST set out to create a system for fast remote certification of high-dose radiation sources against the U.S. national standard gamma-radiation source using the Internet. The Internet-based system promised to deliver immediate certification results to the industry customer on-demand at a lower cost. Through a contract with Advanced Technology Research Corporation, a working alpha version has been assembled on PCs and a server within the Ionizing Radiation Division. Several system design changes were developed along the way. Software changes to the Bruker EPR spectrometer forced a design change in the data acquisition mechanism. Direct control of and communication with the spectrometer is no longer possible. Instead a module will be built in to the spectrometer software by Bruker that will perform the measurements and deliver a secure file to a specified location. This data file will be read by the NIST software to prepare a certification. The NIST has worked out the specifications for the file format and is discussing the new software improvements with Bruker. Other design changes are now obvious. The system can be made simpler and more user friendly by moving the client side dose calculations to the NIST public server. This would allow the NIST to push changes and data to the server without having to rely on the client to make database updates. In 2007 the client and server side software will be installed to create a NIST testbed. The next stage is to transfer the software to Bruker to begin beta testing the *e*-certification system. (M.F. Desrosiers, J.M. Puhl)

Testing a Method for Establishing e-Traceability to NIST High-Dose Measurement Standards. To meet the rapid turn-around time needs, yet maintain high accuracy, and minimal uncertainties, an internet-based system for remote dose certification of industrial radiation sources using a table-top EPR/alanine analyzer is being developed at the NIST. In order to establish traceability to the NIST high-dose measurement standards, each Bruker e-Scan instruments used in industry will be calibrated to the NIST reference dosimetry system/instrument. A comprehensive method for customer-to-NIST-calibration-curve conversion has been established by determining the optimal computational method for detrmining a dosimeter measurement conversion factor (MCF) between the reference and remote instrument calibrations. The uncertainty attributed to applying the MCF in the response conversion has been evaluated and used to establish an overall uncertainty budget for such an internet-based service.

Beta-testing and evaluation is being conducted in order to facilitate the completion of the client-server software system for this Internet-based high-dose transfer dosimetry service. Testing the creation of a the NIST standard reference curve is being conducted by creating multiple insert calibration sets and varying the number of dosimeters measured at each dose point before applying the mathematical-fit to create the calibration curve. This will help increase the accuracy, as well as decrease the uncertainty, associated with creating the standard calibration curve. Utilizing the two separate e-Scan systems at the NIST, testing the calculation of the MCF is being conducted by creating a customer insert set, like that which would be sent during an actual calibration event, and exporting the results in order to perform the MCF calculation. Testing the electronic certification process is conducted by measuring a series of unknown/test dosimeters, applying the MCF and calculating dose from the NIST standard reference curve. These tests will be performed for all of the commercially available inserts, and will serve as guidelines for the operational aspects of this future service. (S.L. Cooper, M.F. Desrosiers, J.M. Puhl)

Electron-Beam Dosimetry Indicators. EB Fast Check Strips were developed by Spectra Group Ltd. The product was described as a simple, reliable, fast and easy to use indicator of the relative absorbed dose of electron-beam and gamma-ray radiation, designed for a simple visual inspection or for use with color densitometer. According to the product literature, the dosimetry strips can be read in a short period of time and do not require extra processing steps (*e.g.*, annealing) and were valid for the dose range 10 kGy –100 kGy. This study examined the strips' dose response, the effects of relative humidity during irradiation, and temporal effects of the response after irradiation. A procedure to quantify the color change was devised and tested using a Minolta Chroma Meter CR-300. It was found that the dose could be easily read over a wide range; however, the accuracy and precision of the visual analysis was poor without the aid of a visual reference chart. Thermal annealing of the dosimeters, to arrest the color development, was needed for quantitative measurements. The working dose range was found to be 5 kGy to 80 kGy, and there might be a dose-rate effect below 3 kGy/h. The dosimeters were highly sensitive to ambient light and mildly sensitive to the relative humidity during irradiation. (M.F. Desrosiers, N. Graneto)

F. HOMELAND-SECURITY APPLICATIONS

Testing of Radiation-Detector Instruments for Homeland-Security Applications. In support of the Department of Homeland Security program at the NIST, a study involving the characterization of a large number of x-ray and gamma-ray detection instruments was done. The measurements were performed at the NIST x-ray and gamma-ray calibration facilities maintained by the Radiation Interactions and Dosimetry Group. The exposure rate and energy response of the detectors was measured over a wide energy range by using calibrated photon beams from ^{60}Co (1.25 MeV) and ^{137}Cs (0.662 MeV) sources, and various highly filtered x-ray beams with mean energies ranging from 0.15 MeV down to 0.06 MeV. End users that benefit from this work, and for whom ANSI standards and Test and Evaluation protocols have been developed, include first responders, Coast Guard, port authorities, and Customs personnel. (R. Minniti, C.M. O'Brien).

X-Ray Security-Screening Standards for Homeland Security. The Radiation Interactions and Dosimetry Group is funded by the Department of Homeland Security (DHS) to develop technical-performance standards for four classes of x-ray security screening systems: checkpoint cabinet, computed tomography, cargo & vehicle, and human subject. Four ANSI working groups have been organized to develop national standards for technical performance, focusing particularly on image quality. The ANSI designations, domain of applicability, and specific image quality metrics that will be assessed are summarized in the table below.

Project Overview: X-Ray Security Screening

Development of image quality standards for DHS

Threat Domain	IEEE ANSI PIN #	Venues	IQI's (Image Quality Indicators) to be tested	IQ test methods & artifacts	Minimum performance requirements ?	Certification / Validation
Checkpoint	N42.44	aviation security, public buildings & events	resolution, penetration, organic-inorganic differentiation, wire- and hole-type IQI's	ASTM F792	YES	TSL
Computed Tomography (CT)	N42.45	screening systems using CT e.g, all checked luggage	radial, tangential, and slice resolution, noise, dual-E accuracy, streak artifact, CT # consistency, belt speed, attenuation	NEW	NO, security sensitive applications	TSL
Cargo/ Vehicle	N42.46	ports, borders, rail, trucks	penetration, spatial resolution, wire detection, contrast sensitivity, & resolution-contrast hybrid metric	NEW	NO, applications too diverse	NTS/DNDO
Human Subjects	N42.47	aviation, events, borders, prisons	TBD	NEW	YES	TSL

Each standard will include both test methods and x-ray phantoms appropriate for the application. Examples of artifacts that are being designed and tested are shown in the accompanying figure. In the upper portion, to test penetration and contrast sensitivity of high-energy inspection systems used to inspect cargo, the orientation of an arrow must be determined through increasing thicknesses of steel. In the lower portion of the figure is an x-ray of a test piece proposed to test the spatial resolution of CT imaging systems.

In related work, this year the group has established 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 disarmament. This is under funding from DHS by way of the NIST Office of Law Enforcement Standards (OLES). The results of testing will be used to establish minimum image-quality standards and will be used to update an National Institute of Justice standard covering these systems. (L.T. Hudson, F. Cerra, P.M. Bergstrom, S.M. Seltzer)

Radiation Safety and Measurements for Security-Screening Applications. The Radiation Interactions and Dosimetry Group is participating in the development of various standards for radiation safety of security screening systems employing x-ray and gamma radiation. In May 2006, the NIST organized a workshop for the purpose of revising ANSI/HPS standard N43.17, "Radiation Safety for Personnel Security Screening Systems Using X-rays." The revision is necessary because of advances in technology leading to many new system configurations. The workshop resulted in the reconstitution of the N43.17 Subcommittee, which held three subsequent meetings organized by NIST staff. In 2006 the Radiation Interactions and Dosimetry Group also helped organize and participated in meetings of the ANSI/HPS N43.16 Subcommittee working on a radiation safety standard for non-intrusive cargo inspections. NIST staff is working on ASTM test methods for measurements of the x-ray exposure to items inside a luggage inspection system and the radiation leakage exposure to bystanders. Laboratory measurements have been conducted in support of these efforts as well as calculations of potential effective doses resulting from the operation of screening systems for luggage and humans.

In December 2006 a comprehensive radiation-safety evaluation of a body scanner was completed under an Interagency Agreement with the Transportation Security Administration. (F. Cerra, S.M. Seltzer, L.T. Hudson, P.M. Bergstrom)

Advanced X-Ray Systems for the Detection of Special Nuclear Materials. The Radiation Interactions and Dosimetry Group is providing support to the Domestic Nuclear Detection Office of the Department of Homeland Security in their Cargo Advanced Automated Radiography System. This system employs only passive x-ray inspection to detect the threat of nuclear material. Our support consists of calculations using Monte Carlo codes and of measurements. The initial calculations and measurements are part of an effort to determine the radiation safety of such systems. (P.M. Bergstrom F. Cerra, R. Minniti, F.B. Bateman)

High-Energy Computed Tomography. This past year saw much progress in the development and improvement of the Division's High-Energy Computed Tomography (HECT) facility. A large effort was undertaken to relocate the entire beam line and imaging system to the east side of the measurement room, thereby reducing radiation leakage rates in the control room by a factor of 20 or more. Once operational at the new location, we began a series of tests to evaluate system performance. These assessments led to the development of improved imaging methods, including the installation of an adjustable mount for the front-surface mirror and the introduction of a high-efficiency scintillator screen to enhance the CCD-camera signal. Plans are underway for the development of a set of test objects to quantify spatial resolution and image contrast.

A number of hardware and software improvements were made as a result of collaboration with engineers from Savannah River National Laboratory. These include the installation of an object manipulation system consisting of a rotating turntable and a two-dimensional linear stage. LabVIEW programs were also developed to interface with and control the CCD camera, manipulate the staging system, and obtain CT reconstructions of the image data. A number of test objects are being assembled which should allow us to evaluate the performance of the HECT imaging hardware and gain expertise in the use of tomographic reconstruction tools. (F.B. Bateman, M.R. McClelland, D.F. Eardley)

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