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, to the meeting of Section I (X and γ rays, electrons) of the Consultative Committee on Ionizing Radiation (CCRI), May 21-23, 2003, Paris. The material was taken from information gathered for NIST program reviews, and covers roughly calendar years 2001 and 2002. 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.

2. TECHNICAL ACTIVITIES

A. THEORETICAL DOSIMETRY

Photon and Charged-Particle Data Center. The Data Center compiles, evaluates, and disseminates data on the interaction of ionizing radiation with matter. The data on photons and charged particles, with energies above about 1 keV, include fundamental information on interaction cross sections as well as transport data pertaining to the penetration of radiation through bulk material. Databases are developed and maintained on attenuation coefficients for x rays and gamma rays, including cross sections for Compton and Rayleigh scattering, atomic photo-effect, and electron-positron pair production, as well as on energy-transfer, energy-absorption and related coefficients relevant to radiation dosimetry. Work on charged-particle cross sections and of radiation transport data has entailed significant effort on the evaluation of the stopping powers and ranges of electrons, positrons, protons, and alpha particles, the elastic scattering of electrons and positrons, and the cross section for the production of bremsstrahlung by electrons. 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 engineering and scientific compendia, books and review articles, and in the reports and protocols of national and international standards organizations. The compilations of the Data Center rely heavily on the synthesis of available theory to extend the data and provide for comprehensive coverage over broad ranges of energy and materials. Thus we have long been involved in complex computational analyses and in the development of highly sophisticated transport-theoretic methods. Our Monte Carlo transport calculations also are incorporated into some of the most widely used general-purpose radiation transport codes. With the help of the NIST Physics Laboratory's Office of Electronic Commerce of Scientific and Engineering Data, a number of the Center's databases can be accessed on the worldwide web. (S.M. Seltzer, P.M. Bergstrom, J.H. Hubbell, M.J. Berger)

Cross Sections for the Elastic Scattering of Electrons and Positrons by Atoms. A new evaluation of cross sections for the elastic scattering of electrons and positrons by neutral atoms has been completed. Results are given for atomic numbers Z = 1 – 100, and for kinetic energies from 1 keV to 100 MeV. For energies up to 10 MeV, the results are obtained from the code of Riley, which calculates phase shifts by the numerical solution of the Dirac equation. Screened Coulomb potentials, used as input, were derived from electron density distributions obtained with the Dirac-Hartree-Fock code of Desclaux. Above 10 MeV a new code was developed that uses the same electron density distributions as input, but is based on the WKB method of Molière as formulated by Zeitler and Olsen. The output tables include differential cross sections at 314 angles, at 61 energies for electrons, and at 41 energies for positrons. Total and first transport cross sections are also included. The basic tabulations are for scattering by free atoms with point nuclei, and neglect exchange and polarization effects. Cross sections for many elemental solids are also tabulated which were obtained with free-atom potentials modified according to a prescription of Raith. Also tabulated are correction factors that take into account (a) the exchange effect for incident electrons (according to an approximation of Riley), and (b) the reduction of the cross sections at high energies and large deflection angles, assuming a nuclear charge distribution according to the Fermi model rather than a point nucleus. An interpolation program is provided that can be used to generate cross sections at any energies and angles specified, for gases or solids, with or without the corrections (a) and (b). A code is also provided which generates transport cross sections of arbitrarily high order needed as input for the calculation of Goudsmit-Saunderson multiple-scattering angular distributions. This work has greatly contributed to the efforts of a report committee on the elastic scattering of electrons and positrons, sponsored by the International Commission on radiation Units and Measurements (ICRU). (M.J. Berger, S.M. Seltzer)

Proton and Alpha Particle Stopping Powers. Our work on the critical evaluation and the preparation of databases of proton and alpha particle stopping powers and related quantities was incorporated into *Stopping Powers and Ranges for Protons and Alpha Particles*, Report 49 of the International Commission on Radiation Units and Measurements, 1993. Those results were recently criticized by another database producer in the journal *Radiation Research* as defective in a number of respects. After a thorough analysis and detailed comparisons, it has been demonstrated that the criticisms are largely erroneous and that the data hold up better than the competing database. A Letter to the Editor documenting this conclusion has been published in *Radiation Research*. (S.M. Seltzer, M.J. Berger)

Compton Scattering of Photons. Activities within the Photon and Charged Particle Data Center have concentrated on the development of a suite of computer programs to evaluate the total cross section for Compton scattering from electrons bound in atoms. The codes that were developed start from the expressions for the cross section doubly differential in scattered photon energy and angle in the impulse approximation (relativistic and nonrelativistic). These doubly differential data, calculated for a given subshell, were integrated over scattered photon energy to obtain the angular distribution of the scattered radiation and, subsequently, over scattering angle to obtain the subshell's contribution to the total cross section. The accuracy of these numerical integrations is enhanced by application of an adaptive Gauss-Kronrod integrator in both integrations. The cross section for the whole atom is obtained by summing over all subshells; the subshell ratios provide additional details of the scattering process of potential interest. Additionally, this code suite is utilized to obtain the Compton scattering component of the energy-transfer coefficient and the mass energy-absorption coefficient. The nonrelativistic impulse approximation has been utilized to obtain total cross sections for all elements in the energy range from 1 keV to 20 MeV. These nonrelativistic-impulse approximation calculations are based on the Compton profiles of Biggs *et al.*. The profiles provide the necessary information to compute cross sections doubly differential in scattered photon energy and angle. As the Biggs *et al.* data are provided on a subshell basis, the resulting cross sections must be summed over all subshells to obtain the whole atom result. These studies are directed towards understanding the effect of Doppler broadening on the total cross section and on the mass energy-absorption coefficient. The relativistic impulse approximation is currently being applied in similar calculations for all elements, and a substantial portion of the database has already been generated. The goal of these activities is to generate comprehensive tabulations of the total and energy-absorption cross sections for Compton scattering that a) are consistent with underlying differential and subshell data, b) will separate out the ionization-only channel in the inelastic scattering amplitude, and c) have well-understood theoretical uncertainties (arising from choice of approximation in the evaluation of the amplitude and in the atomic model employed) and known numerical uncertainties. (P.M. Bergstrom, S.M. Seltzer, J.H. Hubbell)

Wall Corrections for Bragg-Gray Cavity-Ionization Chambers. The absolute determination of the air-kerma rate from gamma-ray beams is typically based on the use of air-filled, graphite-wall, Bragg-Gray cavity-ionization chambers. Such determinations have provided for national standards to which measurements for radiation therapy and for radiation protection have been traceable. In the realization of air kerma, one of the corrections required for such chambers is for the attenuation and scatter of the beam in the wall material, the so-called wall correction. The traditional method to account for these effects is to extrapolate measurements made with chambers of various wall thicknesses (all of which are sufficient to insure charged-particle equilibrium) to zero wall thickness. It has been demonstrated that, in general, this method is erroneous, and that coupled electron-photon Monte Carlo calculations are more accurate. U.S. standards are based on the use of up to eight spherical graphite-wall cavity-ionization chambers, whose wall corrections had been evaluated using the extrapolation method. Taking advantage of their inherent ability to distinguish among energy deposited (ionization) by secondary electrons from primary and scattered photons, we have used Monte Carlo calculations to determine new wall corrections for the NIST chambers, for photon energies pertinent to our standards for ^{60}Co, ^{137}Cs and ^{192}Ir gamma-ray fields. These results will be used to revise NIST standards, as part of an international effort to harmonize standards using the best wall corrections. (S.M. Seltzer, P.M. Bergstrom)

Monte Carlo Transport and Applications. The Radiation Interactions and Dosimetry Group has obtained and installed the major Monte Carlo codes for the transport of photons and electrons on the Group's computational resources. Additionally, we have modified these codes and applied them to problems of interest in computational dosimetry and in imaging. he absolute determination of the air-kerma rate from gamma-ray beams is typically based on the use of air-filled, graphite-wall, Bragg-Gray cavity-ionization chambers. Such determinations have provided for national standards to which measurements for radiation therapy and for radiation protection have been traceable. In the realization of air kerma, one of the corrections required for such chambers is for the attenuation and scatter of the beam in the wall material, the so-called wall correction. The traditional method to account for these effects is to extrapolate measurements made with chambers of various wall thicknesses (all of which are sufficient to insure charged-particle equilibrium) to zero wall thickness. It has been demonstrated that, in general, this method is erroneous, and that coupled electron-photon Monte Carlo calculations are more accurate. U.S. standards are based on the use of up to eight spherical graphite-wall cavity-ionization chambers, whose wall corrections had been evaluated using the extrapolation method. Taking advantage of their inherent ability to distinguish among energy deposited (ionization) by secondary electrons from primary and scattered photons, we have used Monte Carlo calculations to determine new wall corrections for the NIST chambers, for photon energies pertinent to our standards for ^{60}Co, ^{137}Cs and ^{192}Ir gamma-ray fields. These results will be used to revise NIST standards, as part of an international effort to harmonize standards using the best wall corrections. Additionally, modifications were made to the MCNP code to provide an imaging capability, and we have utilized this capability in a preliminary study with ITL to determine the capability of their blind-deconvolution algorithm in eliminating blur in photon scattering. A particularly important application has been highlighted in our response to recent bio-terrorism: anthrax in mail. Considerable effort has been dedicated to the theoretical dosimetry for industrial mail irradiations by electron and bremsstrahlung beams. The results of this modeling informed our experimental approach and aided in timely advice to the US Postal Service and their contract irradiation facilities on radiation-processing parameters to effectively decontaminate the mail and parcels, while minimizing effects due to overdosing. (S.M. Seltzer, P.M. Bergstrom)

B. INDUSTRIAL DOSIMETRY

Response to Bioterror Attacks through the US Mail. After anthrax-laced mail was delivered to media and government offices, resulting in several deaths, illness, mail disruption and economic loss, the Division responded rapidly to identify industrial irradiation of the mail as an effective and ready process to kill anthrax spores. Leading a task force established by the White House Office of Science and Technology Policy (OSTP), NIST worked with the Armed Forces Radiobiology Research Institute (AFRRI), the US Postal Service, and industrial irradiation facilities to provide critical dosimetry measurements for the validation of the process. Based on an extensive program of Monte Carlo radiation-transport calculations, NIST provided advice on the optimization of the processing-system parameters and the strategies to effectively handle the highly variable mail and parcel stream. High-energy electron beam (10 MeV) irradiation was recommended for sanitization of letter mail and “flats” (magazines, catalogues, and newspapers). Informed by the Monte Carlo calculations, the protocol and process were validated by designing a variety of test letter mail that was instrumented with alanine dosimetry from NIST and biological indicators (spores) from AFRRI. The results of these measurements confirmed that the minimum required dose was being deposited and that the distribution of that dose through the product was optimized with respect to overdose. The electron-irradiation process that so effectively sanitizes letter mail was not penetrating enough to be used on the nearly 200 000 larger-volume packages that were quarantined due to possible cross contamination at the Brentwood and Trenton postal facilities. It was decided that 5 MeV x-ray irradiation was the best-available tool for decontaminating parcel mail. Again, NIST traceable dosimetry was used in phantom tests and spore-kill tests to provide quality assurance of the correct dose as required by the bacillus anthracis radiation-kill curves generated by the Armed Forces Radiobiology Research Institute (AFRRI). This expedited the processing and delivery of this large backlog of long-delayed packages. High-dose industrial irradiation continues for prophylactic bioremediation of mail and parcels going to Washington DC federal government offices (ZIP codes 20200 through 20599). And NIST continues in collaborative efforts to improve the processing of mail, entailing the work outlined in the following three paragraphs. (B.M. Coursey, L.T. Hudson, S.M. Seltzer, M.F. Desrosiers, D.J. Alderson)

High-Dose Dosimetry Measurements and Standards for Homeland Security. The NIST Physics Laboratory collaborates under the direction of the OSTP with USPS, DOD (including AFRRI), DOE, FDA and USDA to ensure decontamination of anthrax in mail. Work has included: 1.) Calibration of electron-beam dose rates for the two industrial irradiation facilities used to treat contaminated USPS mail. 2.) Dosimetry of spore-kill validation experiments for the different electron beam parameters at the two industrial irradiation facilities used to treat contaminated USPS mail. 3.) Quantitative analysis of volatile organic chemicals and other potential irritants produced in mail packages during irradiation processing. 4.) Calibration of x-ray beam dose rates used to treat contaminated USPS large parcels. 5.) Dosimetry of spore-kill validation experiments for x-ray beams used to treat contaminated USPS large parcels. 6.) Preparation of mail-irradiation guidelines with AFRRI, FDA and industry representatives through the American Association for Medical Instrumentation (AAMI). (M.F. Desrosiers, J.M. Puhl, S.L. Cooper)

Forensics in Homeland Security. A collaboration between the Physics Laboratory's Ionizing Radiation Division and the Chemical Science and Technology Laboratory's Biotechnology Division produced encouraging data regarding the applicability of existing DNA profiling tests to mail treated with high doses of ionizing radiation. NIST high-dose ionizing radiation sources were used to treat envelopes under conditions approximating industrial processing. These envelopes were analyzed at NIST using standardized DNA tests. It was demonstrated that there is no concern regarding the ability to obtain useful DNA typing results from irradiated mail. Full DNA profiles were obtained from irradiated test envelopes using the FBI's primary DNA test. Moreover, no procedural modifications were necessary, as the standard DNA extraction procedures worked fine for obtaining DNA from envelopes whether or not they have been irradiated. This study was of great interest to the FBI, CIA, US Secret Service and other crime laboratories. (M.F. Desrosiers)

Radiation Effects on Archival Documents. Prompted by concerns about irradiated mail, the National Archives and Records Administration (NARA) approached NIST and the Armed Forces Radiobiology Research Institute (AFRRI) to assist them in the assessment of radiation effects on archival materials. Several meetings included briefings detailing the work-to-date in mail sanitation and VOC studies on irradiated mail, as well as an overview of cellulose radiation chemistry. These were followed by collaborative experiments in which NIST electron accelerators were used to simulate industrial effects for NARA scientific testing. (M.F. Desrosiers, F.B. Bateman, M.R. McClelland, J.M. Puhl)

***e*-Calibration Service Successfully Demonstrated.** Developing a new method for the delivery of measurement services, the Internet will be employed to provide industry with electronic traceability to national standards. This departure from the traditional modes of traceability presents many new challenges. An Internet-based system for fast, remote calibration of high-dose radiation sources against the U.S. national standard has now been created and tested. The traditional mail-based calibration service relies on sending artifacts to the user, who then mails this back to NIST for evaluation. The new service will deliver calibration results to the industry customer on-demand, in real-time, at a lower cost. The industrial site will have a dosimeter reader and an Internet link to the NIST server. When a calibration is requested, the industrial site will connect to the NIST calibration web site and initiate the process. In order to ensure a reliable dose assessment, the NIST server will lockout the local user and fully control the measurements remotely. The remote control process will include the spectrometer calibration, setting of readout parameters, real-time spectral acquisition and validation. The post-measurement evaluation process involves a rigorous verification of the quality of the acquired spectra, and dose calculations from calibration curves maintained at NIST. The calibration results can be rapidly incorporated into the production process to ensure the highest quality in manufacturing. The service offers the U.S. irradiation-processing industry a direct link between industrial processing and the national standard. Moreover, the *e*-calibration service is a technological solution to the Ionizing Radiation Division's rapidly growing demand for industrial calibrations. At a recent ASTM International Workshop on Radiation Dosimetry, an instrument used to perform calibrations was connected to the Internet in the conference hotel in San Diego and was remotely controlled by a NIST server in Gaithersburg. A calibration on the San Diego instrument was performed solely by the NIST server, without the direct involvement of NIST staff. With the fundamental features now in place, additional features and safeguards are being incorporated in the next-generation system before the field testing of this technology. After successful demonstration of the test version of the new Internet-based high-dose radiation calibration service last year, efforts began. The new system has some fundamental design changes from the rudimentary system tested above. The service will no longer require a constantly open high-speed Internet connection between NIST and the remote user; information will be transferred via encrypted files, also eliminating the need to modify NIST and corporate firewalls. These modifications have been enthusiastically received by prospective NIST users of this service. Several industrial partners are poised to begin a collaborative trials at their facilities. These tests should foster confidence in the system prior to its inauguration as NIST's first *e*-calibration service. Electronic calibrations will deliver NIST services in real time, on demand, at low cost. The *e*-calibration service will permit large international companies to be calibrated identically. Moreover, foreign facilities can also subscribe to the service. This will expand the dissemination of NIST standards and facilitate measurement equivalence. Electronic calibrations through the global connectivity of the Internet will serve to harmonize ionizing radiation measurements and facilitate trade. (M.F. Desrosiers, J.M. Puhl)

Radiation-Process Simulation and Modeling Meeting. To facilitate interest in simulation and modeling as an emerging field in industrial radiation processing, NIST hosted a first-ever meeting of RPSMUG, the Radiation Process Simulation and Modeling User Group. RPSMUG's mission is to promote the safe and reliable use of mathematical modeling and simulation technologies as they apply to all elements associated with industrial radiation processing. The group has grown and is planning a follow-up meeting in 2003. (M.F. Desrosiers)

Alanine-Film Dosimetry. A new polymer-based film dosimeter containing alanine has been tested. The film, produced by Kodak, is about to go into production with lot sizes in excess of one million. These films will improve the quality of industrial processing as a rapid and accurate measure of dose. The unique facilities at NIST were used for detailed studies of the radiation-response characteristics with particular emphasis on possible environmental influences. These efforts greatly accelerated the introduction of this film. (M.F. Desrosiers, J.M. Puhl)

X-Ray Measurement Quality Assurance for DoD Large-Motor Inspection Facilities. For the past 21 years NIST personnel have provided x-ray measurement and radiographic expertise in support of the Navy's large-missile-motor inspection programs. Recently the manufacturer of the film that had been used for most component inspections altered the manufacturing processes, requiring that all film inspections need to be re-proofed. With our substantial expertise and history in this program, NIST is participating in this function. A parallel task is the measurement of x-ray energy fluence rates of x-ray generators at the various inspection sites, undertaken to document the equivalency of these inspection sources. The x-ray energy used for component and motor inspections at these sites employ generators whose maximum potentials range from 300 kVp to 16 MeV. NIST personnel developed and maintain a computer-based portable measurement system referenced to the NIST standards to perform these measurements. NIST personnel also provide consulting service to DoD's Integrated High Payoff Rocket Propulsion Technology Program in the development of nondestructive-inspection systems and image-manipulating software to assist US manufacturers in remaining competitive in the world market to supply satellite-launch vehicles. (J.H. Sparrow)

X-Ray Measurement-Quality Assurance for DoD Contractors and Government Large-Motor Inspection Facilities. NIST personnel continue to provide a measurement assurance program for the Navy's high-energy x-ray facilities (420 kVp to 15 MeV) used to inspect large missile motors and component parts. NIST personnel also provide consulting services for the design and use of image-quality indicators (IQI) used in this program. For smaller components, NIST personnel assemble and supply the Navy with the IQI that is used by one of their contractors. NIST personnel also provide consulting services to DoD when updating inspection hardware that is no longer supported in order to address the concern by the DoD that results with the new equipment maintains comparability with all archived inspection images. (J.H. Sparrow)

Progress in Assembly of a High-Energy X-Ray Computed-Tomography Facility. Development continues on beam-line and imaging components for a high-energy x-ray computed tomography (HECT) system on the NIST MIRF 7-32 MeV electron linac. This system will be used in the development of techniques and systems for industrial imaging, including the creation of a testbed facility for cargo inspection. The 42^{o} beam port has been designated for this project. With the use of multiple quadrupole magnets, the electron beam will be re-focused into a circular beam. Two computer programs have been used to predict the placement and field strengths of the focusing magnets needed to achieve the required small electron-beam size at the tungsten target. To facilitate this re-focusing process, a support system is being installed that permits precise movement of the quadrupole magnets along the electron-beam line. The optimum focusing parameters will dictate the physical placement of the tungsten target and its'1800 kilogram lead collimator. In turn, this unit dictates placement of the imaging system that consists of a 15 cm square fluorescent screen positioned 2 meters from the source. A single-bounce 45^{o} front-surface mirror will reflect the transmission-radiographic image into the camera. The camera is a cooled 1K x 1K pixel CCD camera that is housed in a 19 mm thick brass shield and surrounded by 9100 kilograms of lead shielding. The MIRF tomography facility will be unique in that it will be performed at x-ray energies significantly higher than are presently available at other facilities. (J.H. Sparrow, F.B. Bateman, M.R. McClelland, P.M. Bergstrom, S.M. Seltzer)

Accelerator Radiation Sources. Our electron accelerator facilities continue to support active research in radiation-interaction studies. These electron sources include the 32 MV linear accelerator of the Medical and Industrial Radiation Facility (MIRF), the 4 MV Van de Graaff accelerator, and the 500 kV cascaded-rectifier electrostatic accelerator. NIST electron beams are used in a broad array of applications including materials modification, detector calibration and characterization, radiation-hardness studies, production of radioisotopes, radiation treatment of wastewater, and medical and industrial dosimetry. Recently, our accelerator sources have been employed in a variety of measurements including industrial and materials-effects studies as well as some fundamental physics applications. Van de Graaff electron beams were used successfully to calibrate and characterize a backscatter-suppressed beta spectrometer to be employed in a neutron beta-decay experiment. This experiment will probe the physics of fundamental nuclear interactions in an effort to refine and expand the standard model of particle physics. The MIRF and Van de Graaff sources have been used to investigate the shielding properties of various composites at electron energies of 1, 2 and 7 MeV. These results will help to validate the predictions of electron transport models. The Van de Graaff accelerator has also been used to check the radiation response of new and existing types of diodes and solar cells. This research will aid in the design of more radiation-tolerant devices in terrestrial and space radiation environments. Our future plans include a program to measure the low-energy response of radiochromic and alanine dosimeters using the 500 kV accelerator. Recent improvements to the 500 kV facility include a collimating aperture/beam monitoring system for more reliable beam delivery, which ensures that a nearly parallel beam is incident on the samples. We have also developed an automated target-ladder system to cycle samples in and out of the beam continuously, thereby minimizing the effects of fluctuations in beam intensity. We have designed and constructed a Faraday cup that couples to the target ladder, which will aid in dosimetric measurements by allowing the electron beam fluence incident on the samples to be measured directly. Work is underway to develop high-energy e-beam dosimetry standards using graphite calorimeters with the MIRF linear accelerator. Our electron-accelerator facilities continue to be improved and expanded. We recently obtained a beam-position monitoring system for the MIRF accelerator, which will aid in beam delivery and ensure the symmetry of electron and photon radiation fields. Development continues on beam-line and imaging components for a high-energy x-ray computed tomography (HECT) system at the MIRF facility. This system will be used in the development of techniques and systems for industrial imaging, including the creation of a testbed facility for cargo inspection. During this past year we purchased a Clinac 2100C medical accelerator from the Mayo Clinic in Rochester, MN. Installation of this machine is currently underway. Once installed, this machine will significantly expand our programs in medical dosimetry, through the availability of therapy-quality electron and photon beams. (F.B. Bateman, M.R. McClelland)

C. MEDICAL DOSIMETRY

Calibration of Low-Energy Photon-Emitting Brachytherapy Sources. Small radioactive "seed" sources used in prostate brachytherapy, containing either the radionuclide ^{103}Pd or ^{125}I, are calibrated in terms of air-kerma strength using the NIST primary standard, the Wide-Angle Free-Air Chamber (WAFAC). The WAFAC is a 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 350 seeds of twenty-two different designs from fifteen 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 well-chamber response to air-kerma strength 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 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-based air-kerma strength for prostate brachytherapy seeds, emergent x-ray spectra are measured with a high-purity germanium (HPGe) spectrometer. Pulse-height distributions from the spectrometer are unfolded to obtain the true photon spectra emerging from the seeds in the transaxial direction. ^{103}Pd seeds from all six manufacturers have very similar photon spectra, while there are four distinct spectra from ^{125}I seeds produced by thirteen manufacturers. These differences in ^{125}I seed spectra are a result of fluorescence x-rays emerging from those seeds that include silver as support material for the radionuclide. The effect of these fluorescence x-rays is to lower the average energy of the emergent spectrum, resulting in a lower well-ionization chamber current relative to air-kerma strength due to differences in the energy sensitivity of the well-chambers and the WAFAC. Knowledge of seed emergent spectra allows separation of well-ionization chamber response effects due to spectral differences from those due to seed internal structure and self-absorption. To verify that seeds of a given design calibrated at NIST are representative of the majority of those calibrated in the past, several additional tests have been implemented. Mapping of the distribution of radioactive material within a seed using radiochromic-film contact exposures as well as angular x-ray spectral measurements enable characterization of the degree of anisotropy present in seed emissions. The relative response of calibration instruments has been observed to depend on such anisotropy. Transmission x-ray radiography using phosphoimaging-plate detection is used to check for anomalies in seed construction. Data from two Accredited Dosimetry Calibration Laboratories (ADCLs) and the seed manufacturer, in addition to the results of NIST measurements, are compiled and checked as a function of time to ensure the continuous validity of the calibration traceability chain from NIST to ADCLs and manufacturers. (M.G. Mitch, P.J. Lamperti, S.M. Seltzer)

X-ray Spectrometry of Prostate Brachytherapy Sources. To understand the relationship between well-ionization chamber response and WAFAC-based air-kerma strength for prostate brachytherapy seeds, x-ray emission spectra are measured with an HPGe detector. Pulse-height distributions from the spectrometer are unfolded to obtain the true photon spectra emerging from the seeds in the transaxial direction. ^{103}Pd seeds from all five manufacturers emit very similar photon spectra, while there are five distinct spectra emitted by ^{125}I seeds from thirteen manufacturers. These differences in ^{125}I seed emission spectra are a result of fluorescence x-rays emitted by the radionuclide support material, either silver or palladium. The effect of these fluorescence x-rays is to lower the average energy of the emitted spectrum, resulting in a lower well-ionization chamber current relative to air-kerma strength because of the greater energy sensitivity of the well-chambers compared to that of the WAFAC. Knowledge of seed emergent spectra allows separation of well-ionization chamber response effects due to spectral differences from those due to seed internal structure and self-absorption. (M.G. Mitch, S.M. Seltzer, P.J. Lamperti)

LabVIEW Automation of Brachytherapy Dosimetry Measurements. Data acquisition and instrument control for all measurement stations in the NIST beta brachytherapy laboratory (including well-ionization chambers, extrapolation chamber and plastic scintillator) are automated using LabVIEW (National Instruments), a graphical programming language. LabVIEW incorporates DataSocket technology that allows live data transfer between computers over the internet. This can be used in conjunction with a video teleconferencing link, providing a “virtual presence” at NIST for scientific collaborators and calibration customers. Data from instruments at NIST can be passed over the internet to a collaborator's computer, also running LabVIEW, while communication between investigators (and observation of instrument function) is enabled through the use of video cameras and microphones. Such real-time interaction between NIST scientists and their industrial colleagues during a measurement will improve the overall efficiency of collaborative research. (M.G. Mitch, C.G. Soares)

Beta-Particle Emitting Ophthalmic Applicator Calibration Service. With the advent of the calibration service for ophthalmic applicators at the University of Wisconsin Accredited Dosimetry Calibration Laboratory, the routine role of NIST in these calibrations has diminished considerably. Four planar ^{90}Sr and three concave ^{106}Ru/Rh sources were calibrated in 2001; two planar ^{90}Sr sources were calibrated in 2002. NIST's role in this field will henceforth be more geared towards providing transfer-standard sources and fields both to secondary laboratories and to source manufacturers. The results of the major international intercomparison of ophthalmic applicator dosimetry, which included the dosimetry of both curved and flat sources of ^{90}Sr/Y and ^{106}Ru/Rh was published in Medical Physics and are included in the ICRU report on beta particles for medical applications. A new high-sensitivity electrometer has been purchased to allow measurement of lower-activity sources with this system, and its integration into the current measurement system has begun. An intercomparison of high-dose-rate beta-particle dosimetry between NIST and PTB was completed using a PTB secondary standard; preliminary results indicate agreement of the two laboratories within the quoted uncertainties. (C.G. Soares)

Intravascular-Brachytherapy Source Dosimetry. The use of beta-particle-emitting brachytherapy sources for the prevention of restenosis (re-closing) of coronary blood vessels after angioplasty continues to be actively explored. NIST has taken an early and leading role in the calibration of the sources used for this therapy, employing the NIST extrapolation chamber equipped with a 1 mm diameter collecting electrode to measure dose rate at a depth of 2 mm in water-equivalent plastic. These measurements are confirmed using radiochromic-dye film, which is also used to characterize sources in the cylindrical geometry for transaxial uniformity. In addition, irradiations of planar sheets of film at various depths in water-equivalent plastic are used to construct data sets that can be used to predict the dose rate at arbitrary locations around the sources using a modified form of the AAPM Task Group 43 protocol. The equipment used for these studies is augmented with two micro-scintillator detection systems, two automated three-dimensional water-tank scanning systems, various well-ionization chambers, and two small fixed-volume ionization chambers. Collaborations were continued between NIST and Guidant, Inc., for dosimetry of their ^{32}P wires, and more than 10 sources and over 400 of their well-ionization chambers were calibrated. Collaborations also continued with Novoste, Inc., for dosimetry of ^{90}Sr/Y seed trains; 13 sources were calibrated, and a measurement-assurance proficiency test was performed with two AAPM secondary laboratories for these sources. Collaborations were inaugurated with Radiovascular for the calibration of their ^{32}P-shell source, with Medtronic for the calibration of their miniaturized x-ray sources and with Xoft, also for calibration of miniature x-ray sources. Calibrations were also performed on the PTW OPTIDOSE scintillator system for use in verifying reference absorbed-dose rates at the clinical level. Coupled with the continuing collaboration with Photoelectron Corporation for the calibration of their x-ray probes, it is anticipated that these collaborations will lead to a new standard for low-energy photon absorbed-dose measurement. A new collecting electrode with a much better defined collecting area was designed at NIST for the NIST extrapolation chamber, using a novel conducting plastic. Investigations into the divergence effect, as well as the effective area of the collecting electrode, are expected to reduce the currently large uncertainty in the NIST calibration of beta-particle brachytherapy sources by about a factor of two. (C.G. Soares, M.G. Mitch)

Dissemination of Absorbed-Dose-to-Water Standards. A decade ago, the work of Steve Domen on the development of a sealed-water calorimeter culminated in 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 the Accredited Dosimetry Calibration Laboratories (ADCLs) to the medical physics community. This supports the new dosimetry protocols that are based on absorbed dose to water rather than air kerma. NIST has a second-generation Domen calorimeter, designed and constructed with more modern components and computer-based control and data acquisition. With the commissioning of our new strong ^{60}Co source, the calorimeter will be tested and refined with the goal of establishing the instrument as the national standard for absorbed dose to water. This will make possible calorimeter measurements in beams other than ^{60}Co (e.g., high-energy x-ray beams from accelerators, proton beams) for the direct calibration of instruments used in therapy, and will facilitate a broader range of international comparisons. (J. Shobe, H. Chen-Mayer)

Development of a New X-Ray kVp Calibration Service. The NIST Ionizing Radiation Division is in the process of developing a new x-ray beam kV calibration service. The plan is to offer calibrations of devices used to measure the accelerating potential applied to x-ray generators. A precision voltage divider, calibrated by EEEL and traceable to the NIST primary standard for voltage, will be installed on the x-ray generators used in the NIST x-ray beam calibration range, covering constant accelerating potentials up to 300 kV. Customers can submit devices to be irradiated in NIST beams of their choice. Such devices usually are based on some indirect measurement, such as the differences in transmission among x-ray filters of different compositions and/or thicknesses. The results from the device will be reported along with the measured accelerating potential, with an accuracy anticipated to be typically 1 kV or better at the 95% confidence level. (C.M. O'Brien)

X-Ray Calibration Range Upgrades. The Group maintains and develops national measurement standards for air kerma (exposure), in the form of free-air chambers, and x-ray beam qualities from conventional W-anode generators and from mammography (Mo- and Rh-anode) generators for instrument calibrations. We have three x-ray calibration ranges, 10-to-100 kVp conventional, 100-to-320 kVp conventional, and mammography, together offering some 80 beam qualities. The 10-to-100 kV W-anode x-ray tube has been replaced, and all the NIST and ISO reference radiation qualities have been reestablished. The beam uniformity remains the same, and all x-ray beam half-value layers are reproduced. The 100-to-320 kV x-ray tube was also replaced. The new tube is a different design, featuring less inherent filtration and a slightly larger focal spot. All NIST reference radiation qualities have been redeveloped without changing the additional filtration appreciably and with no change to the operating tube potential. The four BIPM reference beam qualities produced at 100, 135, 180 and 250 kVp have now been developed at NIST. These will be used for an indirect comparison with BIPM planned for this February of 2003; this indirect comparison will be a repeat of measurements performed in 1991. A recently obtained voltage divider has been calibrated at NIST and used to verify the operating voltage of the x-ray generators. A second voltage divider will be integrated into the system, allowing the direct measurement of voltage on both the cathode and anode of the 320 kV system. After a voltage calibration of the second voltage divider, both calibrated dividers can be used to accurately determine voltage and to calibrate non-invasive kVp meters. (C.M. O'Brien)

D. PROTECTION AND ACCIDENT DOSIMETRY

Gamma-Ray Sources Used for Radiation-Protection Calibrations. Five gamma-ray sources are used for calibration of instruments and passive dosimeters in terms of air-kerma and exposure, to support protection-level measurements in the US. The calibrations are directly traceable to measurements with the national primary standard for gamma-ray exposure, graphite-cavity ionization chambers. The ranges provide a wide range of air-kerma rates. Two ^{137}Cs sources provide air-kerma rates from 4.5 mGy/h to 110mGy/h; a third ^{137}Cs source provides air-kerma rates of 2.3 Gy/h and 3.6 Gy/h; and two ^{60}Co sources provide air-kerma rates from 0.25 mGy/h to 5.4 mGy/h. In addition, two ^{60}Co teletherapy-level sources are available to extend the range to much higher rates. Programs of regular, calibrated exposures of thermoluminescent dosimeters provide direct support for the worker-protection measurement programs of a number of agencies, including the US Navy. NIST standards are also disseminated through a number of secondary instrument calibration laboratories to provide traceability of protection-level measurements. (R. Minniti, P.J. Lamperti, J. Shobe)

Development of a Low-Level ^{137}Cs calibration Range. The design and assembly of a new calibration range has been completed. The range will be used for the calibration of ionization chambers and other gamma-ray detection instruments at very low air-kerma rates. Currently, the lowest ^{137}Cs air-kerma rate available at NIST is 5 mGy/hr. The present development will provide for NIST-traceable calibrations at air-kerma rates down to 5 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. After some additional work to characterize the new range at the lowest air-kerma rates, comparison measurements will be conducted with secondary standard dosimetry laboratories before announcing the availability of this new NIST service. (R. Minniti, S.M. Seltzer, P.J. Lamperti)

Validation of the EPR Method for Tooth-Enamel Dosimetry. Knowledge is required on dose-effect relationships for radiation-induced stochastic and deterministic effects. Therefore, the acquisition of dosimetric effects from populations with chronic exposure is of special interest (Chernobyl, Techa River, etc.). Electron Paramagnetic Resonance (EPR) is the only physical method available to retrospective biological dosimetry studies. Validation of the method and rigorous analysis of critical steps is essential before these data can be used reliably in epidemiological studies from which recommendations are made for occupational exposures. Significant effort has gone into developing sound protocols for the preparation of tooth-issue sample for EPR analysis, and into the analysis and interpretation of the EPR results. The long-term objectives of this work are to validate the EPR dose assessment methods for enamel and dentin. (A.A. Romanukha, M.F. Desrosiers, V. Nagy)

Tooth-Enamel Bio-Dosimetry. A final report to the National Cancer Institute summarized the reconstructed doses for 72 teeth collected from population of eight villages located in vicinity of Semipalatinsk nuclear test site (SNTS), *e.g*. Dolon, Kanonerka, Karaul, Novopokrovka, Bolshaya Vladimirovka, Korosteli, Sarzhal, Kainar. The residents of those villages were exposed to one of these three nuclear tests: 08/29/49, 09/04/51, and 12/08/53. The minimum average dose to a village was about 140 mGy; this value is more than double the background dose expected for an unexposed population from this region. The maximum average dose was approximately 250 mGy. (M.F. Desrosiers)

Imaging Plate Dosimetry. The imaging plate contains a photo-stimulable phosphor that is a sensitive two-dimensional detector of ionizing radiation. Following exposure, the plate is placed into a reader where its surface is scanned with a laser, releasing photo-stimulated luminescence, which is then converted into a two-dimensional digital image. Phosphoimaging technology is currently used in applications such as radiography and the measurement of source activity distributions. Preliminary studies at NIST have suggested that the imaging plate can be successfully applied to dosimetry measurement problems involving low dose rates, on the order of 1 μGy/s, inaccessible by radiochromic film. Such a low-level dosimeter would be very useful, for example, in characterizing dose distributions from new, low-activity brachytherapy sources. The imaging plate is now being used to characterize the distribution of ^{90}Sr in teeth from members of the Techa riverside population from 1945-1949, exposed to radioactive waste from the Mayak nuclear weapon plant near the Techa River, Urals, Russia. (M.G. Mitch, A.A. Romanyukha, C.G. Soares)

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 beta sources were calibrated both at the Physikalisch Technische Bundesanstalt (PTB) and at NIST, allowing a direct intercomparison of calibrations. The systems are also being used for the dosimetry characterization of a photo-stimulatable luminescence phosphor imaging system. The standardized techniques developed at PTB and NIST are now included in an International Organization for Standardization (ISO) draft standard and are being implemented in the NIST calibration service. A new high-sensitivity electrometer has been purchased to replace the 15-year old high-sensitivity electrometer currently being used for these measurements. (C.G. Soares, M.G. Mitch)

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