A Review of the 40-Year History of the NSREC'S Dosimetry and Facilities Session (1963–2003)

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***Abstract*—Year after year the Dosimetry and Facilities Session has been a fixture in the Nuclear Space and Radiation Conference (NSREC). As well as being home to subjects absolutely fundamental to dosimetry such as radiation transport, energy deposition, and X-ray photoemission, this session often included newly introduced topics such as hardness assurance and experimental techniques. This review paper describes the 40-year history of this session, whose title changed constantly over the years to reflect new developments. We have attempted to follow the logical chronological development and simultaneously give the reader a pedagogical tour through the main technical areas. Because of the wide variety of subjects in this session, this review covers first the context and background, and then four major subcategories as follows: the development of dosimetry devices and techniques; the basic physics of dosimetry and electron-photon/material interactions; neutron dosimetry and reactor facilities; and bremsstrahlung sources and other radiation facilities.**

I. BACKGROUND: WHAT WORK OVER THE YEARS HAS BEEN PRESENTED IN THE DOSIMETRY AND FACILITIES SESSION?

OF COURSE we know the answer. The Dosimetry and Facilities Session at the NSRE Conference has included papers relating to measuring dose, i.e., the energy absorbed in materials and devices when exposed to radiation. But, one might ask, if we still have this topic today at the NSRE Conferences, does that mean it has taken 40 years to learn how to measure dose? That is, have we not learned how to do this job yet? Well, mostly we have. However, when one reviews the 40-year history of this session there is surprising complexity. In addition, this session has often included a wide range of related topics. This may be noted to some extent by simply looking at the various titles this session has had over the years. As shown in Table I, surprisingly, there have been 18 different names (a separate session did not appear in the years 1965 and 1967).

These titles tell a story in that the session title was usually the session chair's intentional choice to reflect the main body of work that year. For example, in the early years of the conference, researchers needed accurate methods of measuring dose and primary photocurrents from pulses of ionizing radiation. Hence, the title in 1966 was "Experimental Techniques and Dosimetry." In the late 1960s and early 1970s a major area of study focused on neutron damage in transistors, as may be seen in the 1972 title, "Radiation Dosimetry and Neutron Energy Dependence." Occasionally, the subject matter often included papers only remotely related to dosimetry. In 1974, it was "space radiation effects" and in 1975 it was "hardness assurance" included along with dosimetry.

In the 1980s, there were many papers focusing on energy deposition, photoemission, transport code development, and dose enhancement. These were all key subjects in the understanding of most radiation effects measurements, whether recording and understanding device responses or in recording the necessary dosimetry data. In the late 1990s these papers declined in number as the radiation transport field matured and many more papers on microdosimetry began to appear. Papers on facilities would come and go as various organizations in the community constructed new experimental capabilities.

As in any conference, the sessions change as the technologies evolve and new effects are discovered. The total number of papers per year for each of the major subdivisions in this review paper is plotted versus time in Fig. 1.

II. DEVELOPMENT OF DOSIMETRY DEVICES AND TECHNIQUES

The history of radiation dosimeter development may, to some degree, be tracked simply by looking at the papers on the subject as published in the TRANSACTIONS ON NUCLEAR SCIENCE (TNS) Proceedings of the NSRE Conference. This observation is surprising since dosimetry is very much a separate discipline for which there exists an international community of reactor and accelerator developers, of nuclear engineering, health physics and medical researchers, and for many years, a dosimetry community, all quite independent of the radiation effects community. On the other hand, researchers in the NSREC community, even from the earliest days, would first make use of what dosimetry was available and then, as the need arose, make improvements or invent new methods. This section covers a short history of dosimeter devices as evidenced by the 40 NSRE conferences. We have divided this part into three subsections: A) basic dosimetry devices (1964–1975); B) dosimeter improvements (1976–present); and C) advances in micro-dosimetry (1982–present).

Readers who are in need of assistance in understanding terms and definitions are referred to two excellent NSREC short courses on dosimetry given by Klaus Kerris in 1986 and 1992 [1]. These short courses are also an excellent starting point for material on how to select and use a dosimeter, information not readily available in any one location and of great value to

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TABLE I
A 40 YEAR HISTORY OF THE DOSIMETRY SESSION TITLE

Year	Session title	Number of papers
1964	Radiation Effects Dosimetry	4
1966	Experimental Techniques and Dosimetry	4
1968	Special Device Effects and Energy Deposition	5
1969	Energy Deposition and Dosimetry	7
1970-71	Dosimetry and Energy Deposition	7, 8
1972	Radiation Dosimetry and Neutron Energy Dependence	8
1973	Radiation Dosimetry, Measurement Standards, and Quality Assurance	8
1974	Dosimetry, Space Radiation Effects, and Hardness Assurance	8
1975-76	Hardness Assurance and Dosimetry	8, 9
1977-78	Simulation, Energy Deposition, and Dosimetry	14, 14
1979	Energy Deposition and Dosimetry	8
1980	Dosimetry and Radiation Transport	5
1981	Energy Deposition and Dosimetry	12
1982	Energy Deposition, Dosimetry, and Radiation Transport	13
1983-84	Radiation Transport, Energy Deposition and Charge Collection	10, 11
1985-91	Dosimetry and Energy-Dependent Effects	13, 15, 10, 10, 7, 6, 8
1992-94	Dosimetry and Radiation Facilities	4, 8, 6
1995	Radiation Metrology and Facilities	5
1996-97	Dosimetry	10, 6
1998	Radiation Dosimetry	6
1999-2002	Dosimetry and Facilities	5, 7, 6

anyone planning experimental work. We repeat a couple of key definitions here in Table II.

Other invaluable resources include the collection of American Society for Testing and Materials (ASTM) testing standards [2]. The ASTM publishes individual guides or "practices" for almost all dosimeters and dosimetry methods. There are also various books on dosimetry and radiation effects [3].

A. Basic Dosimetry Devices (1964–1975)

The first paper in the first-ever "Dosimetry" session at NSREC was "Dosimetry for Radiation Damage Studies," by Rossin [4]. This paper described neutron dosimetry (which will be covered in Section IV of this review paper) with a good introduction to neutron damage effects and steps outlined for "determining and reporting fast neutron exposure." We next mention the second paper in this first dosimetry session because the author, Kloepper [5], gives a wise admonition to all who would conduct radiation effects experiments. Kloepper says, "All too frequently determination of the "effect" is pursued much more diligently than the determination of the correct dose rate, in spite of the fact that the functional dependence of the effect on the dose rate is no better determinable than the accuracy of the dynamic dosimetry." Kloepper is also the first to point out at NSREC the importance of making sound measurements in a mixed radiation field (gammas and neutrons). Needless to say, as we will see in Section IV-D, this mixed field issue is still with us today.

The first decade of NSRE conferences included many papers describing various dosimeters and dosimetry applications. Table III gives a list of different dosimeters, the year presented and published at NSREC, the first author, the application area, and advantages and disadvantages.

B. Dosimeter Improvements (1976–Present)

Some of the techniques shown in Table III did not prove to be convenient or accurate enough to survive the test of time and are no longer in use today. Other dosimetry methods, such as CaF_2 thermal luminescent dosimeter (TLDs) (although $CaF_2:Mn$ instead of $CaF_2:Dy$) and Si calorimeters are still utilized today.

Of course, developing new and improved dosimeter devices remained a constant goal in the radiation effects community. Table IV gives a list of those improvements and includes a number of new techniques for measuring dose and dose rate. The development of high dose-rate flash X-ray sources in this time period motivated the need for dosimeters that could read high dose rates and also operate in radiation environments. The "improvement" period started in the mid 70s and continues to this day. Notice that most of the papers in Table IV were published in the period of 1976–1984. (In what could be argued to be an arbitrary division, we treat the emergence and rapid growth of *microdosimetry* devices in the 1980's through the early 2000s separately in Section II-C.)

Occasionally, there were important dosimeters that were not presented at NSREC. Perhaps this occurred because these devices were adequately covered in other conferences. One such device is the calibrated PIN diode. PINs are very convenient, fairly inexpensive, and remain in widespread use today for dose and dose rate measurements. More recently, photo-conducting detectors (PCDs) are also used for this purpose. PCDs are sometimes preferred over PINs because of their very fast [subnanosecond (ns)] temporal response [27].

Starting in about 1981, there was an increase in the number of papers that addressed important issues connected with dosimeters already in use by the NSREC community. Occasionally, problems were reported. For example, it was discovered in 1981 that there could be delayed darkening in certain radiochromic dye films [28], which, if not taken into account, would lead to erroneous dosimetry results. Sometimes detailed studies led to increased confidence in using certain dosimeters in one radiation environment but not in another. For example, in 1982, high temperature trap studies in LiF TLDs showed that X-ray and gamma-ray irradiation had similar glow curve results, but ion

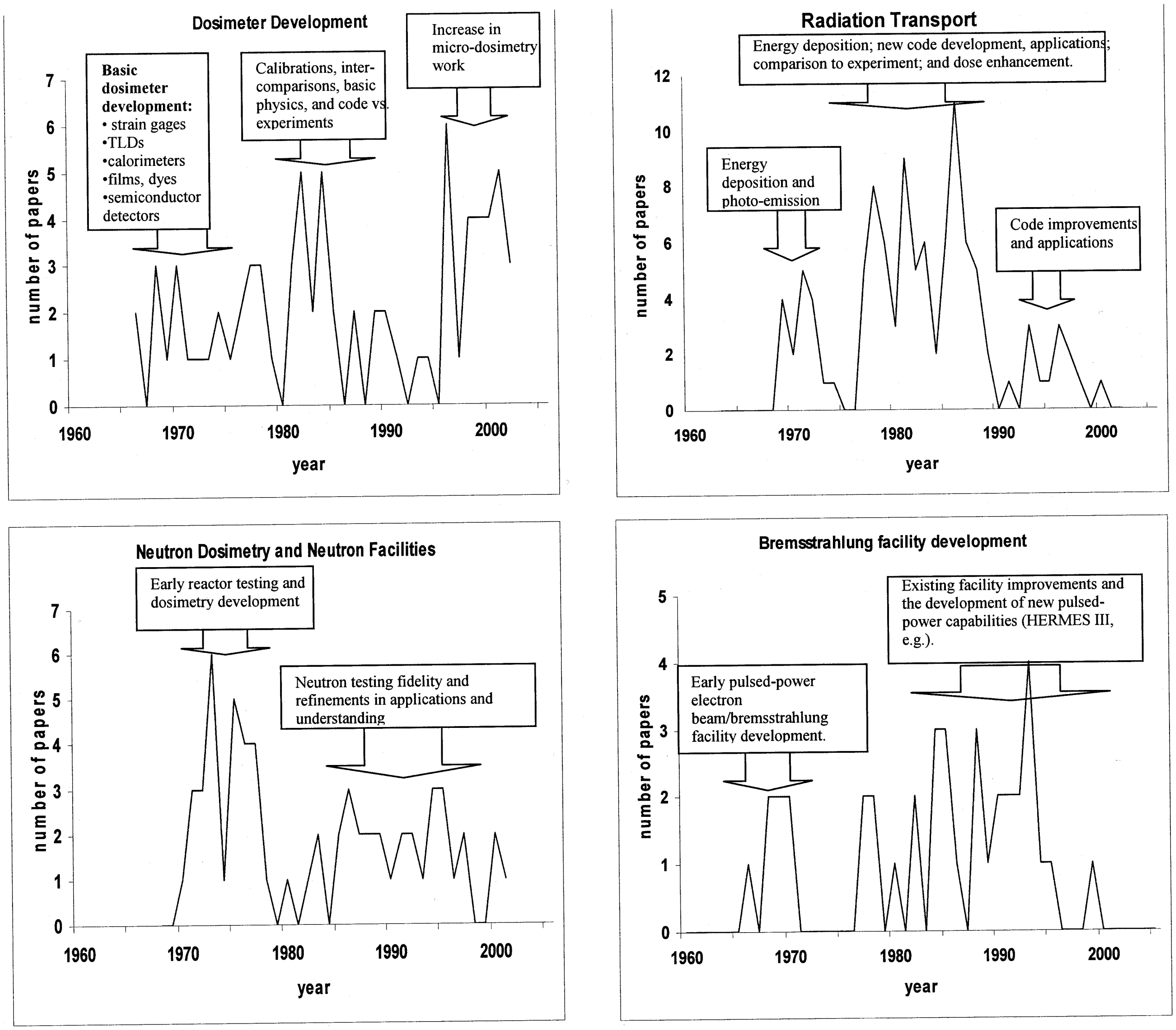

Fig. 1. Number of papers per year versus year for the four subcategories of this Dosimetry Session review paper. Different subthemes are noted in the boxed captions.

and neutron irradiation produced quite different curves [29]. It was concluded that more work was needed to extend LiF TLDs to neutron dosimetry. Several years later, in 1988, it was shown that LiF doped with Mg exhibited a super-linear behavior before saturation [30]. Special precautions had to be taken and some experimenters probably avoided LiF dosimeters for this reason.

The interesting work of Holmes-Siedle and Adams (see Table IV) also continued in the 1980s with additional examinations of how to improve the low dose performance of MOS dosimeters [31]. Actual satellite flight data also proved valuable in advancing MOS dosimeters as common-use devices [32].

There was an important paper in 1982 that called attention to dosimetry errors caused by dose enhancement from low-energy components in X-ray and Co-60 sources [33]. The fix was to reduce the low-energy photons by use of a filter. This paper may have helped stimulate additional work in dose enhancement effects.

From 1982 to 1985 there was an important series of papers discussing the issue of the damage equivalence of gamma rays, electrons, and ions in MOS and bipolar transistors. These papers reported, in general, that electrons and ions produce more damage than Co-60 photons [34]–[37]. People concluded that great care had to be exercised when using electrons and ions with MOS devices (see Section III-C-4).

With the extremely significant experimental discovery of single-event phenomena there was an increased interest in the effects of single ions on pn junctions and in the so-called “funneling” effect. In 1984 an interesting paper by Zoutendyk and Malone [38] described experiments that further illustrated the physics of the depletion region depth’s affect on charge collection due to funneling. Using a Silicon Surface (Schottky)-Barrier Detector (SSBD) they measured the charge collection from alpha particle bombardment. They discussed both prompt (drift) and delayed (diffusion) charge collection and how the extension of the field past the depletion layer leads to full charge collection, an effect called “field funneling.” This paper nicely illustrates how increased understanding of charge collection processes aided several different disciplines within

TABLE II
SEVERAL BASIC DOSIMETRY DEFINITIONS (AFTER KERRIS, 1992 [1])

Term	Definition
Absorbed dose	The mean energy absorbed per unit mass of irradiated material. If ΔE_D is the mean energy imparted by ionizing radiation to matter of mass Δm, then: $D = \Delta E_D/\Delta m$. Also called total dose. The SI unit is 1.0 Gy = 1.0 J/kg. The most used unit of dose is the rad, where 1.0 rad = 100 erg/g. (1.0 Gy = 100 rad).
Absorbed dose rate	The time rate of change of the absorbed dose, dD/dt.
Particle fluence	The number of particles incident on a sphere of unit cross-sectional area. $\Phi = dN/dA$ (cm^{-2}).
Linear energy transfer (LET)	LET is the important dosimetric parameter used in the study of single-event upsets (SEU). Two commonly used definitions and corresponding units are: Mass stopping power, ($dE/dx/\rho$) ($MeV\cdot cm^2/mg$) Energy deposited per unit path length ($MeV/\mu m$)

TABLE III
LIST OF DOSIMETERS USED IN THE EARLY YEARS (1964–1975)

Type	Year, First author [ref.]	Application(s)	Advantage(s)	Disadvantage(s)
PZT ferroelectric	1964 Hester [6]	Gamma-ray and x-ray dose	Minimal response to neutrons. High dose rates.	Limited range and loss of polarization during irradiation.
Glass slides	1964 Fridell [7]	Dose	Inexpensive.	Fading and limited range.
PZT ferroelectric and filters	1967 Miller [8]	Differential energy spectrum of flash x-ray source	Measures energy spectrum at high dose rates.	Needs unfolding. Early version of Gorbic's spheres. Using filters goes back to 1933.
Polymers	1967 Judeikis [9]	Dose	10^3-10^8 rad range.	Too difficult to read. Requires EPR system.
Strain gage	1968 Birdsall [10]	Dose	Measure expansion of material of choice.	Not accurate at low doses.
Chemical methods	1970 Klein [11]	Dose and dose rate	Can measure pulses via fast reactions in liquids.	Needs laser to measure fast absorption.
Radiation sensitive plastics	1970 Harrah [12]	Electron beam deposition	Used to measure e-beam deposition profile in dielectrics.	Accuracy.
CaF_2:Dy TLDs	1971 Sukis [13]	Dose	Passive and wide range.	Each batch must be individually calibrated. Super-linearity and fading were problems in the early years.
Dye polychloro-styrene thin films	1972 Chapell [14]	Dose	High dose rates	Calibration
LiF TLDs	1974 Fairchild [15]	Dose	Wide dose range	Questions on high dose and super-linear behavior not understood.
Si calorimeter	1975 Wrobel [16]	Dose	Gives direct dose to silicon	Success is very dependent on proper design.

the NSREC community, in this case dosimetry and single-event effects.

Also starting in this 1980s time period, there was a notable increase in the use of analysis and radiation transport codes to improve or better understand certain dosimeters and their applications. The following papers are examples: 1) X-ray films were studied with a variety of photon energies and the results were compared to Monte Carlo calculations [39]; 2) calculations of cosmic-ray-and radiation belt proton-induced radioactivity in Ge gamma-ray detectors were made to study the ultimate limit of spectrometer sensitivity, without and with shielding [40], [41]; and 3) Monte Carlo predictions of active detector responses were used to better understand measured responses [42] and further validate radiation transport codes such as the Integrated Tiger Series (ITS) [43].

C. Advances in Micro-Dosimetry (1982–Present)

Microdosimetry theory was first applied to radiation effects in microelectronics by Burke *et al.* [44], [45]. They, along with researchers in radiation biology, recognized that at sufficiently small volumes, because of the "graininess" of the flux of incident particles, the dose is not a well-defined quantity. Energy deposition becomes a stochastic quantity, and it must be described by a statistical as well as spatial distribution function. The discovery of single-event upset (SEU) effects and the rapid increase in satellite and space applications accelerated the demand for a better understand of localized energy deposition. One of the first papers to develop a computer model for calculating the energy deposited in a small micro-volume was Farrell and McNulty [46]. They considered the need to develop systems that could withstand SEU effects in space environments and,

TABLE IV
LIST OF NEW OR IMPROVED DOSIMETERS (1976–PRESENT)

Type	Year, First author [ref.]	Application(s)	Improvement(s)	Advantage(s)/Disadvantage(s)
Si microcalorimeter	1976, Lynch [17]	Dose	Extended range of 10 rad(Si) - 10 krad(Si)	Speed and dose to Si.
Compton diode	1977, Longmire [18]	Measurement of Compton current density	New	Does not need collimation of Compton current before measurement
Thin-film resistor (bolometer)	1977, Roche [19]	X-ray energy deposition	New	High signal levels, easy application. / Energy losses must be considered.
MOS dosimeter	1978, Adams [20]	Dose	New use. Also, first use of MOS dosimeter in space	Weight, power, and size. / Sensitivity an early issue.
MNOS dosimeter	1978, Fraass [21]	Dose	New use.	Wide range of 10 krad(Si) to 4 Mrad(Si)
Fiber optic dosimeter	1978, Evans [22]	Dose from reading color darkening	New system incorporating LED read package.	Small, light weight.
CMOS technology MOS dosimeter	1981, Dawes [23]	Dose	Improved MOS ionization dosimeter. New use of CMOS technology.	Can be integrated with rad-hard ICs. Range of $5x10^3$ to $5x10^5$ rad(Si)
PMOS FET dosimeter	1984, August [24]	High dose LINAC testing	Extend MOS dosimeter to a Mrad.	No obvious LINAC dose rate dependence.
MOSFET dosimeter	1997, MacKay [25]	Low dose rates in space.	Applied improved sensitivity dosimeters in space.	Measure small doses (less than 0.10 cGy)
Stacked PMOS dosimeter	1998, O'Connell [26]	Dose	Improved bulk bias control method.	Achieved high sensitivity.

in their paper they gave a useful description of microdosimetry when they wrote, "The goal of microdosimetry is to determine the number of electron-hole pairs generated within a volume element having specified microscopic dimensions following exposure to radiation." Many papers followed in subsequent years. Work included modeling of electron-induced cluster generation in SiO_2 [47], meson energy deposition in Si [48], dose fluctuations with proton irradiation [49], charge deposition in thin Si slabs [50], calculations of energy deposition in micro-volumes from proton irradiation where recoils from nearby regions dominate [51], and the development of a microdosimeter system with built-in filters for space applications [52].

LiF TLDs were also studied from the microdosimetry point of view. An examination of the detailed track interactions in LiF TLDs provided insight into the supralinearity in heavy charged particle irradiations [30]. Work also continued in space dosimetry where microdosimetry concepts are very important in understanding single-hit particle effects [48].

During the last six years there has been a continuing strong emphasis on microdosimetry development [53]–[56]. Although this recent work often focused on space dosimetry, there has also been a notable increased emphasis on medical microdosimetry. Other applications have included high-energy accelerator and ion microbeams microdosimetry. Examples are: 1) Bradley, *et al.* [57] who improved micro-volume definition using SOI technology; 2) Rosenfeld, *et al.*, who developed "edge-on" MOSFETs for profiling ion microbeams with as high as ~ 1 μm resolution [58], [59]; and 3) Cornelius, *et al.*, who developed and applied an ion transport code to simulate ionization energy deposition in microscopic volumes [60].

Starting in about 1998, the group led by Dusseau [61]–[64] presented papers that described the development of a new microdosimetry technique based on optically stimulated luminescence (OSL). This method has the advantages of high resolution and wide range (see Table V).

III. BASIC PHYSICS OF DOSIMETRY AND ELECTRON-PHOTON/MATERIAL INTERACTIONS

A. Introduction

In this section, we focus on the physics of electron/ photon transport because transport is often the basic starting point for understanding dose in materials. In particular, we survey work in the areas of: basic theoretical and experimental studies of transport, dose enhancement and related phenomena, X-ray photoemission from surfaces, and radiation charging and conductivity of insulators. It should be emphasized that the need to understand applications like dosimetry (including dose enhancement), X-ray photoemission and the design of radiation simulators is what drove organizations and the NSREC community to focus on understanding the physics of electron/photon transport. Papers in the transport area include development of theoretical models, benchmark experiments, and applications to problems of radiation effects on materials, dosimeters, and electronic devices. There has been a continual feedback between the basic physics and the applications and, as a result, NSREC papers provide a rich mine of information in these areas.

We wish to note that that NSREC studies of electron/photon transport heavily utilized knowledge and concepts developed in seemingly unrelated fields such as radiation therapy physics and cellular biology. Examples of this include ionization chamber dosimetry, cavity theory, transition zone dosimetry (equivalent to dose enhancement), and microdosimetry and track structure.

TABLE V
SUMMARY OF THE OPTICALLY STIMULATED LUMINESCENT (OSL) DOSIMETER BY L. DUSSEAU, *et al.* [61]–[64]

Dosimeter Type [ref.]	Application(s)	Improvement(s)	Advantage(s)
OSL films [61]-[63]	1. Evaluating packaging 2. As dosimeter in satellites	1. Dose-depth determination 2. In-flight readout capability.	Optically Stimulated Luminescence (OSL) has wide range (10 μGy-10 Gy) and reset capability.
OSL films [64]	High-energy particle physics dosimeter	50 μm resolution.	Can reset dosimeter often to obtain high doses without saturation.

In turn, the work by the NSREC community has made an impact on these and other fields such as radiation processing, improvements in radiation dosimeters and detectors, and accelerator shielding.

B. Physics of Electron and Photon Transport

In this section, we survey NSREC papers covering basic interactions, electron slowing-down (energy-dependent transport), mathematical methods, computer codes, transport calculations, and experimental measurements. Calculations of the transport of electrons and photons can sometimes be treated separately, but, as radiation source energies exceed 100 keV, interactions in which photons produce electrons (e.g., Compton- and photoelectrons) and vice versa (e.g., bremsstrahlung) cannot be neglected. Hence, the transport of *coupled* electrons and photons must be considered in most applications.

1) Basic Interactions and Electron Slowing-Down: During irradiation, whether by electrons, X-rays, or gamma rays, e.g., electrons and photons transport into the materials and are absorbed, change direction, or lose energy. The strength of the scattering or energy loss is represented by a cross section (or, equivalently, a mean free path) or a stopping power for the particular interaction. Examples of these interactions include, for example: 1) elastic and inelastic scattering by electrons and 2) in the case of photons, scattering, and absorption coefficients as a result of photoelectric, Compton, and pair-production interactions.

Several early studies and theoretical predictions were made of these fundamental interaction parameters and these parameters, in turn, have been used as inputs to electron/photon transport codes (usually Monte Carlo). Examples of parameters that were studied include: electron mean free paths and stopping powers for low-energy electrons [65]–[70], electron range [71], and bremsstrahlung cross sections [72]. Theories of electron straggling [73]–[75] and electron multiple scattering [76] were also formulated.

In 1969, Birkhoff gave an important invited paper [77] in which he reviewed the status of experimental data and theory regarding electron slowing-down. In the experiments electrons were injected into materials by a radioactive source distributed within the material and the energy spectrum of emitted electrons (from around 1 MeV down to a few electron volts) was measured. The interesting feature of electron-slowing-down was that the spatial and angular aspects of the transport of electrons could be ignored and only the energy spectrum of the electron flux in the material was important. By integrating the appropriate interaction cross section (such as K-shell ionization) multiplied by the electron flux spectrum, the relative number of events, such as K ionizations, became clearly evident as the electrons lost energy [78], [79].

2) Mathematical Methods, Computer Codes, and Transport Calculations: Several mathematical methods were developed to study transport. A finite-difference solution of the Spencer–Lewis transport equation in the continuous-slowing-down approximation was reported in 1973 [79]. Fourteen years later, a discrete ordinates solution of this equation in two-dimensional (2-D) formulation was given [80]. Then a different equation, the Boltzmann equation, was numerically solved at low electron energies using a matrix-eigenvalue solution method and was used for predicting soft X-ray photoemission [81], [82].

Also in the mid 1970s, Dellin and MacCallum and collaborators [83]–[85] developed an analytic solution to the transport equation for computing photo-Compton currents. An orthogonal polynomial expansion procedure for obtaining smoothed Monte Carlo distributions was then employed [86], [87] to yield X-ray photoemission angular distributions. Next came an empirical algorithm for computing charge deposition profiles due to electron beams [88].

Perhaps the most important contribution to the physics of electron/photon transport was work starting in the early 1970s to develop comprehensive computer codes for calculating transport phenomena such as energy and charge deposition, bremsstrahlung generation, and X-ray photoemission. In particular, Monte Carlo codes such as POEM [89], TIGER [90], [91], and the Integrated Tiger Series (ITS) [92] and codes that numerically solve the transport equation (CEPXS/ONETRAN [93], [94] and CEPXS/ONELD [95]) were developed and reported in NSREC conferences and other issues of the IEEE TRANSACTIONS ON NUCLEAR SCIENCE.

A more recent code, MITS, (developed at the Sandia and Los Alamos National Laboratories) combines features of CEPXS/ONELD and the ITS Monte Carlo codes [96], [97] and enables adjoint calculations to be made by the Monte Carlo method.

3) Experimental Code Validation and Applications: Code validation and improving one's understanding of an experiment has always been important and many comparisons between electron/photon transport calculations and experimental data have been reported at NSREC conferences. For example, a three-dimensional Monte Carlo code SANDYL [98] was used to calculate the gamma-ray energy deposition spectrum in silicon dosimeter [99]. Starting in 1976, a long series of papers focused on ITS Monte Carlo predictions and experimental measurements to validate ITS and to apply ITS to optimizing bremsstrahlung sources [100]–[107]. In the same time period, for the purpose of understanding differences in dose enhancement profiles obtained with different ^{60}Co gamma-ray sources, Monte Carlo calculations of photon spectra from a variety of sources with widely different geometries were performed [108], [109].

CEPXS/ONELD transport calculations were performed to determine the photon spectrum from a large shielded X-ray test cell (LEXR) [110]–[112]. Finally, the CEPXS/ONELD code was used to compute photon transport through material layers to check the methodology of an ASTM standard [113], [114].

It is important to note that the code applications such as those just mentioned relied on many years of careful experimental work. For example, a large number of measurements of energy deposition profiles due to electron beams with energies of about 1 MeV and above were reported beginning in 1969 [115]–[122]. The studies conducted by Lockwood *et al.* [117]–[121] were designed as benchmark experiments for validating the dose profiles calculated by the ITS codes. Several electron range and electron beam transmission measurements were also made [123], [124] and the response of Ge radiation detectors to X-rays was studied [125], [39]. Other experimental transport studies are listed in Sections III-C and III-D.

C. Dose Enhancement

1) Introduction: For gamma-ray or X-ray irradiation it is important to perform dose measurements under the condition of *charged-particle equilibrium*. Charged particle equilibrium occurs when the electrons moving out of a given region are replaced by an equal number of electrons with the same energy spectrum entering the region. When this condition applies, the dose is simply the product of the photon flux (at a given photon energy) times the photon energy absorption coefficent for the dosimetry material. Charged particle equilibrium is assumed to hold when a dosimeter is surrounded by material of about the same atomic number as the dosimeter. Dose enhancement at a high Z/low Z interface is an important example where charged particle equilibrium dose not hold. The ratio of the dose at the interface to the equilibrium dose is called the "dose enhancement ratio."

2) Experimental: In a ground-breaking paper, Wall and Burke [126] found that when a slab (thick compared to an electron range) of a high Z (such as gold) located next to a thick slab of a low Z material (e.g., aluminum) is irradiated by ^{60}Co gamma-rays, dose values a factor of two times the equilibrium dose can occur near the high/low Z interface. The shape of the dose profile near the interface differed greatly depending on whether gamma rays approach the interface from the high Z or the low Z side.

Frederickson [127] found similar results using secondary electron emission chambers. Charge deposition profiles near high Z/low Z interfaces were also studied [128] in which current measurements were made in a series of seven thin metal foils sandwiched between equilibrium thicknesses of high Z and low Z material. This data showed a divergence of electron current and, hence, a net charge deposition in the regions next to a high Z/low Z interface irradiated with gamma-rays.

Lowe *et al.* [129] demonstrated how low-Z material added in front of a ^{60}Co beam greatly increases the low-energy component of the incoming photon spectrum (through strong Compton scattering) leading to a much larger dose enhancement. This underlined the need to determine the low-energy scattered photon part of the photon spectrum from a ^{60}Co cell (which is strongly geometry dependent).

In response to this need, a simple method for determining the low photon energy content in a ^{60}Co spectrum was developed [130]. The ratio of the ionization current for in a gold-walled chamber to that of an all-aluminum chamber provided a measure of the "purity" of the photon spectrum; the lower the ratio, the purer (unscattered) is the source. An improved method [131] was developed using a simple dual-cavity ionization chamber made of aluminum and a gold foil measured the dose enhancement ratio at interfaces directly. The effects of reversing photon direction and of placing lead or wax between the ^{60}Co source and the chamber to alter the photon spectrum were clearly shown using this technique.

More recent experiments have focused on determining the dose enhancement from different ^{60}Co sources under various shielding conditions. Simons *et al.* [132] made dose measurements with and without gold-flashed kovar lids in a room ^{60}Co source to determine the effect of Compton scattering from the walls of the room. A Pb/Al filter box [33] was used to determine its effectiveness in reducing dose enhancement. Other experiments [133] were performed at Air Force Research Laboratory with a ^{60}Co spectrum measured to have a very small low-energy photon component. Lead bricks which are often used to reduce the dose rate were found to introduce a major low-energy photon component in the spectrum shape. A shielding box consisting of layers of Pb/Sn/Cu/Al was also investigated. The additional Sn and Cu layers suppressed X-ray fluorescent peaks generated in the Pb, Sn and Cu and reduced the low-energy photon component more than the Pb/Al box [132].

3) Theory: A large number of papers describing calculations and modeling of dose enhancement have been given at IEEE-NSREC over the period of 1975–1996. The first [134] described Monte Carlo calculations using the POEM code [89], [135] performed for two interface systems, Si next to Au and polyethylene next to Au. Calculations were performed for the current and dose profiles in each low Z material from 10 keV through 2 MeV for both photon directions. Curve fitting the current profiles for the separate contributions from Compton, K-photo and L-photo electrons, using the functional form $A\exp[-(Bx + Cx^2 + Dx^3)]$, gave good analytic representations of the dose.

Subsequently a semi-empirical model by Burke and Garth [136] employing profile functions of the form $A\exp[-Bx]$ was developed. Equations for A and B in terms of the photon absorption coefficient, the CSDA electron range and electron backscatter coefficients agreed well with the A and B fit coefficients of [134]. An additional term taking into account electrons generated in the low Z material and backscattered from the high Z material was found by Chadsey [137]. This versatile model was applied to predict X-ray photo-emission

[138], X-ray lithography at soft X-ray energies [139], [140] and, more recently, to bremsstrahlung-induced dose enhancement in satellites [141], [142].

Because the exponential model [135] failed to reproduce the shape of the dose profiles far from the interface, a diffusion equation approach was explored [143]. Also, since the model did not take into account directional effects on dose profiles observed at ^{60}Co energies, the model was extended [144] to the high-energy (anisotropic) case using a P_2 transport equation model with exponential solutions. This one-dimensional (1-D) model was programmed for a personal computer [145], [146] and showed promise as a rapid method for calculating dose enhancement, even in arbitrary multilayered structures.

Calculations of dose enhancement with state-of-the-art transport codes such as TIGER [147], CEPXS/ONELD [148], and CEPXS/ONEBFP [141] have also been performed. Other theoretical studies include calculations of charge deposition profiles near interfaces using the POEM code [149], a transport equation solution for dose profiles produced by a Cu X-ray tube operated at 45 kV [150], fitting experimental ^{60}Co dose profiles of Wall and Burke [126] by varying the photon spectrum [151], [152], dose enhancement in GaAs next to Au [153], and dose profiles in Si-SiO$_2$-Si structures for 8-keV X-rays using a special low-energy Monte Carlo transport code [154].

4) Dose Enhancement in Devices: In 1982, Long *et al.* [155] gave an introductory description of dose enhancement in devices in which engineering estimates of dose enhancement factors were given for various package and metallization configurations. This work followed an earlier study of packaging effects on transistor radiation response that had been given by Berger and Azarewicz [156].

Many other studies of dose enhancement in devices have also been reported. Many papers compared the device responses between irradiation using ^{60}Co and 10 keV X-rays [157]–[165], while others involved ^{60}Co alone [166], 10 keV X-rays alone [167]–[172], flash X-ray sources of various types [173]–[178], and a 145-keV average energy bremsstrahlung source [179].

For a discussion of the radiation response of MOS devices the reader is referred to a review paper in this same journal volume by Oldham and McLean [180]. They review the important topics of electron-hole generation, the rapid sweeping out of electrons, the dependence of hole yield on electric field in the oxide, recombination models, dose enhancement, and hole transport, trapping and annealing. Therefore, even though a number of the key papers in this subject area appeared in the NSREC Dosimetry session, we restrict the discussion here.

D. X-Ray Photoemission

1) Introduction: X-ray photoemission refers primarily to the total electron yield or current emitted from a metal surface irradiated by X-rays or gamma rays. X-ray photoemission is important as the driving term or source term for electromagnetic fields set up in a volume by a pulsed beam of X-rays or gamma rays. This is the phenomenon of internal electromagnetic pulse (IEMP).

As far as the energy spectrum of photoelectrons is concerned, we note that electrons generated near the surface lose less energy than electrons produced further from the surface, so that they contribute the highest energy photo-emitted electrons. Also, photoelectrons generated by gamma rays tend to be very forward directed compared with those created by, say, 100 keV X-rays. A problem for predicting both the energy and angular distribution of photo-emitted electrons is that the energy-angular distribution of the electrons generated by the Compton and photoelectric interaction is not well known.

2) Experimental: Experimental measurements of absolute photo-yields began with the work of Bradford [181] in 1972 wherein the X-ray spectrum from a tungsten anode at 50 kV was used to determine absolute electron yields of photo-emitted electrons from Ta, Mo, Cu, and Al. A follow-on paper in 1973 [182] compared measured photoelectron energy spectra for several materials with Monte Carlo calculated spectra using the POEM code. Measured photo yields were 17%–27% above the POEM predictions.

Bernstein and Paschen [183] measured forward and backward photoemission from X-rays in the 10–100 keV energy range from thin metal foils as a function of atomic number for nine metals. Photoemission yields in the soft X-ray region of 1–2 keV [184] were studied using a magnetic spectrometer, and the energy spectra of photoelectrons were measured for aluminum using 1.74- and 1.49-keV X-rays. The total yields were compared with theoretical predictions of Strickland [185] and Burke [186].

Using a magnetic spectrometer and bremsstrahlung spectra from a 50-kV tungsten X-ray tube, Aeby and Whan [187] made photoelectron energy spectrum measurements down to 0.1 keV. Using a filtered X-ray spectrum, their photoelectron spectrum measurements agreed well with those of Bradford [181] and Dolan [188] above 1 keV. QUICKE2 code photo-yield calculations [189] were around a factor of 2–3 lower than measurements. These discrepancies were attributed to the inability of QUICKE2 to calculate electron transport below 10 keV. In the same year, 1981, Chervenak and van Lint [190] reported the results of flash X-ray photoemission experiments. They measured photoemission from thick metal foils and from metal wires for a flash X-ray spectrum. The unfiltered spectrum was close to a black-body spectrum with average energy of 65 keV. A Cu filter was used to harden the spectrum. Their predictions using the photo-Compton current data of Dellin and MacCallum [191] were lower than the measured photo yields by 30%–50%.

Finally, a comprehensive comparison of experiment with photoemission predictions using three different theoretical models enabled Ballard *et al.* [192] to focus on the cases where theoretical predictions gave good agreement with data and those that did not. Experimental measurements of net photoemission yield from various metal and insulator slabs were performed using flash X-ray bremsstrahlung spectra with endpoint voltages of 860 kV and 620 kV. Forward and reverse photoemission for low Z materials and forward photoemission from high Z materials were found to agree well with predictions from all three codes, but code predictions over-predicted the reverse emission yield by up to a factor of 3 for high-Z materials. The reason for this discrepancy is not yet understood.

3) Theory/Calculations: Various theoretical models and transport codes have been used to predict X-ray photoemission, particularly photoemission yields. In an early paper [193], a straight-ahead transport approximation was used. Integral expressions for the X-ray photo-yield from the direct photoelectric process, Auger electrons, and fluorescence-produced photoelectrons were evaluated for several cases. Engineering estimates of the forward, backward, and net photo yield from thin foils of Cu and Au were plotted versus photon energy from 1 to 1000 keV.

Over the years, several transport theory approaches have been applied. As discussed before, the POEM Monte Carlo code by Chadsey [86], [89] was originally developed for calculating photoemission yields. A semi-empirical model for calculating photoemission at soft X-ray energies (similar in type to the model [136] for dose enhancement) was presented by Burke [138] in which good agreement was obtained with published experimental data. Strickland [81] and Strickland and Lin [82] performed theoretical calculations of X-ray photoemission at kilo electron volt energies using solutions of the Boltzmann transport equation. Theoretical calculations for X-ray spectra from exploding wire radiators with photon energies between 1 and 3 keV were compared with experimental results and found to agree better with Al than with Au. Better agreement was obtained with published data for monochromatic X-ray sources.

Finally, in 1988, Lorence [94] developed an improved version of CEPXS, known as CEPXSP, which incorporated the more detailed inner shell relaxation physics used in the Monte Carlo code TIGERP (part of ITS [92]). Using CEPXSP and ONETRAN, he made comparisons with the X-ray photo-yield data of Ballard [193]. Predictions were identical with CEPXS for photoemission yields from low Z materials, but slightly better agreement with experiment for reverse photo-yield from high Z materials was obtained. He proposed that certain forms of electron energy loss not included in TIGERP or CEPXSP may need to be included to improve agreement with experiment.

E. Insulator Charging and Conductivity

Understanding and being able to predict the electrical response of insulators is difficult but is of great importance for radiation effects on defense and space system electronics. A well-known example is spacecraft charging [194]. In this section, we summarize work done by several members of the NSREC community in measuring and predicting the charging behavior and radiation-induced conductivity [RIC] of insulators.

A series of papers [195]–[199] by Frederickson and coworkers were published dealing simultaneously with mathematical modeling of insulator charging behavior and experimental studies of radiation-induced conductivity and insulator charging behavior at photon and electron beam energies around 1 MeV and above. In the case of photon irradiation, a Monte Carlo and analytical study of an X-irradiated semi-infinite insulator next to a high-Z metal was presented by Chadsey [200] and charge build-up in gamma-ray irradiated insulators was studied experimentally [201]. Electron energy deposition profiles in insulators were measured [12], [202], [203] and a combination Monte Carlo–Poisson solver model developed [198]. A theory of radiation-induced conductivity [204] and several measurements of RIC in polymers have been reported [196], [205], [206]. Experiments using electrons in the 1–100 keV range [207], [208] were also performed.

IV. NEUTRON DOSIMETRY AND REACTOR FACILITIES

The neutron dosimetry contributions to the NSRE Conference started out very sparsely from 1964 through 1970, but then erupted in the early seventies as displacement damage became a very important concern for bipolar junction transistors. This interest in the area of displacement damage matured from the determination of a standard damage metric into defining the energy-dependence of the damage function and into an exploration of the damage equivalence for different particles (e.g., neutron equivalent damage from electrons, protons, heavy ions) as well as in nonsilicon semiconductor materials. The interest in displacement damage also led directly into a concern about hardness assurance for the semiconductor industry. Hardness assurance required understanding of the important process controls but, more importantly, regular testing and inter-comparison of test facilities. This concern produced many papers on methods of spectrum characterization, both experimental and theoretical, and on published characterizations of new facilities that offered unique testing opportunities for radiation hardened technologies. Throughout this period the conferences offered a forum for the presentation of new concepts for neutron dosimetry.

A. 1-MeV Equivalent Displacement Damage

The first neutron dosimetry concern was the establishment in the early 1970s of a standard for neutron displacement damage effects in semiconductors [209]–[211]. There was some controversy over the nature and even the ability of the community to set a standard metric for displacement damage. While we all take the metric of 1-MeV(Si) displacement damage as a given, there was serious consideration in the early seventies of using a standard 14-MeV reference point rather than 1-MeV [209], [212]. The 14-MeV standard had the virtue of being readily tested at DT neutron sources and not being an energy located in the middle of a silicon cross section resonance, as is 1-MeV. One of the reasons that the 1-MeV reference energy was adopted was that weapon effects dominated the applications of concern at this time and 1-MeV was closer to the neutron energies of concern. Another concern was the fidelity and universality of the neutron damage equivalence. Conrad in 1971 [209] observed "Some individuals are concerned that the 14-MeV specification may lead others to the erroneous assumption that accompanying ionization may be characteristic of 14-MeV rather than the actual spectrum in question."

Once the reference neutron damage metrics were established, concern shifted to defining the energy-dependence of the neutron damage. The initial work used ENDF/B-IV cross sections [213]–[217]. Work reported in the NSRE conference series led to establishing an ASTM standard for neutron damage, E722, in 1980. After the seventies, the neutron energy-dependence was fairly well established but periodic updates in the available silicon cross section evaluations led to refinements in the energy-dependence of the silicon damage, ENDF/B-V by Luera [218], and ENDF/B-VI by Griffin [219] These refinements were typically soon reflected in revisions to the ASTM standard.

As the energy-dependence was being established, a great deal of attention was spent on better understanding aspects of damage equivalence. In 1975, Van Lint [220], in his initial work in this area regarding neutron, proton and electron damage, observed, “It is recognized that accurate universal correlation between these particles cannot be achieved, because the damage effects of these particles are qualitatively different.” The issue of concern was associated with the different residual defects (interstitials, vacancies, various types of defects) from the cascades produced by the different particles. Over a period of time, papers at this conference resolved discrepancies in the dosimetry at test reactors [221], improved silicon cross sections, and refined the energy-dependence of the damage function. Over this period, the name used to characterize this damage metric also changed from “displacement damage” to a calculated quantity, “displacement kerma,” and more recently has been referred to as “nonionizing energy loss (NIEL).” The accepted community position for damage equivalence in silicon in 1988 was, as stated by Summers, *et al.* [222], “... here is a linear dependence of the experimental displacement damage factors on nonionizing energy deposition for all particles (including neutrons) and for all energies.” As a result of much work, one can see a radical shift from van Lint’s initial observation in 1975 to this 1988 consensus. The linearity of displacement damage for different particle types has even been demonstrated for changes in the transition temperature of superconductors [223]. But it seems that dosimetry topics never actually end, they mature and metamorphise. This 1988 community consensus only covered silicon since there was still debate over GaAs damage equivalence [224], [225]. Conrad [209] observed in 1971 that, “Even though the 14- to 1-MeV ratio seems the same for carrier removal and for lifetime loss in bulk materials, strange things happen when materials are put in devices. Those that degrade by carrier removal may not behave in the same way as those that degrade by a loss of lifetime.” While there is still agreement over the damage equivalence in silicon bipolar semiconductors, rather than closing the damage equivalence issue, recent work [226] examining a universal damage factor for dark current in silicon devices notes a significant difference between low LET particles (photons and low-energy electrons) and higher LET particles (neutrons, pions, protons, heavy ions) in the linear relationship between the thermal generation rate and the displacement damage dose. So, neutron damage in semiconductors continues to be a topic of active research.

B. Hardness Assurance

From the very initial concerns about neutron damage, hardness assurance procedures were recognized as being critical to the industry [227]–[231]. The statistical behavior of devices complicates one’s ability to easily quantify the hardness assurance of parts. Two approaches have been pursued [229]: 1) “test a small sample, assume a distribution for the radiation behavior, ...and apply a statistical extrapolation” and 2) “use physical relationships to establish a lower bound on the radiation behavior.” Both approaches are grounded in gathering experimental data at test facilities. Hardness assurance is such a basic concern to the whole radiation effects community, and not just to the dosimetry component of this community, that it has often appeared at NSRE Conferences as a session separate from the Dosimetry session. The basic characteristics of the high purity silicon used as a material for a device as well as the uniformity and consistency of these characteristics is a component of a hardness assurance program. These characteristics play a large role in the neutron and gamma response of the dosimeter [232]. As the neutron damage equivalence was being established, the testing community refined the hardness assurance screens [233] and started a process of inter-comparison for facilities used to validate neutron hardness [234], [235]. The neutron sources are typically divided into three categories, a moderated TRIGA reactor spectrum, a fast burst reactor spectrum, and a 14-MeV accelerator-driven source. The inter-comparison of damage delivered by these categories of radiation hardening test facilities is still a mainstay of the hardness assurance community. Efforts are made to clearly establish traceability back to national standards, typically in the form of ^{252}Cf spontaneous fission sources [236].

C. Spectrum Determination and Facility Characterization

Recognition of the importance of high-fidelity neutron spectrum determination was present from the very first papers published in this dosimetry session [237]. Initial spectrum determination work used fissionable microspheres (^{235}U, ^{238}U, ^{237}Np, ^{239}Pu) attached to thermocouples. The unavailability of ^{237}Np and enriched ^{239}Pu dosimeters made it difficult for some facilities to use these dosimeters. Proton recoil detectors soon augmented these fission detectors [237]. Gamma sensitivity of the proton recoil detectors limited their usefulness for low-energy neutrons ($<\sim$100 keV). Neutron leakage limited the use of proton recoil methods for high-energy neutrons. Since neutron fluence was not a limitation for most test reactor environments, foil activations methods soon became the most common method for reactor spectrum determinations [238]. The methods for doing activation measurements for specific reactions as well as the important considerations in performing a spectrum determination soon made their way into community standards. Iterative spectrum determination methods such as those used in the SAND-II code, used an input “trial” spectrum and were generally called “unfold” techniques. Least squares based approaches such as used in LSL, required an *a priori* spectrum with quantified uncertainties and were called spectrum “adjustments.” New spectrum determination approaches reflected in dosimetry work include maximum entropy algorithms, neural nets, and genetic algorithms.

The publication of environments for new test facilities was an outgrowth of the hardness assurance procedures and the interest in damage equivalence. Facility characterization is an item of long-standing and ongoing interest to the NSRE Conference [236], [239]–[244]. Even from the earliest work, facility spectrum characterizations emphasized the importance of uncertainty estimates in the resulting spectrum and in derived integral metrics. Advances in dosimetry cross sections and in spectrum adjustment techniques [245]–[247] are reported in this forum and assist in refining the spectrum determination, better quantifying all sources of uncertainty, and in reducing the associated uncertainties. The improved spectrum determinations provide feedback to the facility characterization and inter-comparison activities.

D. New Dosimeter Concepts/Applications

The development of new neutron dosimetry concepts has been a steady but low-level feature of the NSRE Conference. In fact, in 1966, in the very first neutron paper in dosimetry at the NSRE conference, Weng [248] addressed the use of lithium fluoride TLDs as a neutron dosimeter. Furthermore, one of the most recent papers [249] addressed silica optical fibers as mixed neutron/gamma neutron dosimeters. When TLDs are used in reactors, an important issue is the separation of the neutron and gamma response. Early work used LiF TLDs, but in water moderated reactors even the use of enriched ^{7}Li (99.993%) leaves enough ^{6}Li with its very high thermal neutron cross section and a much higher energy deposition per particle interaction that the result was a significant neutron response. Some work has examined the use of the details of the LiF TLD glow curves to unfold the neutron and gamma components of the dosimeter. $\mathrm{CaF_2:Mn}$ is the most common type of TLD used today in test reactors, but the mixed field (n/γ) response of these TLDs is still a matter of some research activity. 2N2222A transistors were used as neutron dosimeters in the early reported silicon damage studies and they continued to be important for inter-comparison studies. Since 1-MeV(Si) dosimetry has been a critically important area, new approaches to measuring this metric without a full spectrum characterization have been proposed [250]. Both neutron and gamma sensitive dosimeters are important to the testing community. The most acute challenge to the reactor test community is the separation of the mixed neutron and gamma response of a specific dosimeter. While most activation foils [246] provide a neutron-only sensitive dosimeter (foils such as $^{115}\mathrm{In}(n,n')$ with a gamma/gamma-prime interference component or ^{235}U fission with a photofission interference product are an exception) it is very difficult to find a gamma-only sensitive dosimeter. Sometimes the shape or intensity of the ionization deposition can be used to distinguish the LET of the source particle. As the community interest went from bipolar devices to CMOS devices, MOSFETs were proposed as promising dosimeters in mixed neutron/gamma fields [251], [252].

E. Miscellaneous

This NSRE conference dosimetry session has also served as a forum for many other topics in the area of neutron dosimetry. Areas in this miscellaneous category include neutron effects on CCDs/CIDs/focal plane arrays [253]–[255]; SEU [247], [256], [257]; and damage cascade modeling [258], [259].

V. BREMSSTRAHLUNG SOURCES AND OTHER RADIATION FACILITIES

With regard to conducting radiation effects experiments on electronics, the actual nuclear or space radiation environments are often expensive and sometimes impossible to obtain. (In the case of nuclear environments, a testing moratorium called a halt to underground testing in 1992.) Therefore, in order to assess the performance or perform phenomenological investigations on the response of electronic devices, it is often advantageous to build radiation facilities that can simulate to some degree the working environment of the device. This section deals with issues related to ionizing dose facilities as presented at the NSRE conference's dosimetry and facilities session over the years. These facilities include ^{60}Co and other radioactive sources, CW X-ray tubes, pulsed bremsstrahlung sources, electron linear accelerators (LINACs), ^{252}Cf sources and cyclotrons. The ^{60}Co and CW X-ray tubes are typically used to examine total ionizing dose phenomena. The pulsed bremsstrahlung sources and LINACs are used for ionizing dose rate phenomena. ^{252}Cf sources and cyclotrons are typically used for SEE.

The papers in this area can be divided into four categories: 1) improvements in ionizing dose facilities and the characterization of their radiation output (12 papers) [111], [130], [273], [280], [281], [283]–[289]; 2) dosimetry and spectrometers developed for the characterization of the radiation output of these facilities (11 papers) [16], [17], [58], [260]–[262], [264], [267], [276], [277], [290]; 3) simulation fidelity issues and instrumentation for electronics testing at these facilities (10 papers) [12], [177], [178], [263], [265], [270], [271], [274], [278], [282]; and 4) the use of radiation transport codes to design these facilities (7 papers) [101], [107], [266], [268], [269], [272], [279], including related code validation work (6 papers) [102], [104], [105], [106], [115], [275]. As can be seen from this breakdown of topics and number of papers, the characterization and appropriate utilization of these facilities is of equal or greater interest than the facilities themselves. This observation is not unexpected considering the nature of this conference.

A. Facilities and Their Radiation Output

The majority of the papers in this subtopic deal with high-energy flash X-ray facilities such as Aurora [286], [287], [289] and HERMES III [280], [281], [283]–[285]. One reason for this concentration is that the design of many of the medium-energy X-ray facilities became export controlled in the 1980s. However, for these high-energy facilities we can track the increase in capability and improved characterization from the 80s to early 90s as improvements were made to the facilities to shape the time history and increase the output of the machines. Indeed, as will be seen in the code section (V.D.), one can observe that the designs for these facilities were being formulated years prior to actual construction. The surviving facility (HERMES III) is the largest area and highest dose-rate gamma-ray simulator in the United States and these papers provide an excellent documentation of its capabilities.

Other papers in this category include descriptions of a ^{90}Sr source [288], a medium energy flash X-ray source [273], a low-energy CW X-ray tube [111], and the characterization of the low-energy component of ^{60}Co sources [130] (note the discussion in Section III-C-2).

B. Dosimetry and Spectrometers

For medium- and low-energy X-rays the task of correlating the dose in the dosimetry with the dose in the device under test depends critically on the knowledge of the X-ray spectrum. For the flash X-ray facilities this is often not well known because traditional detectors such as NaI, cannot be used due to saturation. Two papers deal with inferring the spectrum from depth-dose profiles [261], [277], another uses time of flight measurements of Compton electrons [276], and a third uses machine electrical diagnostics and a code [267]. Finally, an early paper confirms at a low fluence source that bremsstrahlung is produced as expected from radiation transport using traditional counting techniques [262].

Four papers on dosimetry in flash X-ray and electron beam LINAC environments describe the difficulties in making measurements in these environments along with descriptions of the designs of new dosimetry, particularly calorimeters [6], [16], [260], [264]. Although PIN diodes are still in common use today, little emphasis was placed here. For the most part, a Si calorimeter, which could be used at lower doses (1–10), was seen as the optimum dosimeter for device testing in the pulsed environment.

Finally, two recent papers on dosimetry in the newer environments of the cyclotron for SEE [290] and the X-ray microbeam [58] reflect the shift in emphasis in facilities that are utilized today.

C. Simulation Fidelity Issues

A number of papers mentioned earlier deal with testing issues at ionizing dose facilities and, therefore, some are mentioned again here. When conducting experiments it is very important to understand device response issues. For example, one should understand the variations of device response to 10-keV, X-ray, proton, electron, and ^{60}Co irradiations [274], [278] and the dose-enhancement variations from different facilities [177]. There are also important testing issues with cable response [263], dielectric charging [12], and the measurement of device damage at these facilities [271]. Finally, there are papers concerning subtle but yet very important testing issues that have caught many an experimenter by surprise. These are: differences between cyclotron and ^{252}Cf heavy ion testing [270], using gamma ray simulators for SREMP testing [265], dosimetry concerns for lower energy ($<$15 MeV) electron beams [282], and dose enhancement at gamma ray simulators [178].

D. Radiation Transport Codes

Radiation transport codes are also essential for the development of radiation test facilities. The emphasis here is not the design or development of radiation transport codes, but their use for radiation facility design or to correlate dosimetry with the devices under test. In addition, the codes were also validated often specifically for these applications. Some of the validations for the radiation output were also performed for many of the facility characterizations mentioned in the category A above.

One can also see the seeds of some of the innovative diode designs used in our modern radiation facilities that were first described in papers using radiation transport codes for design purposes. Relativistic beam transport [266], [268], reflexing diodes [107], multiple converter diodes [101], source filtering [269], converter design [272], and the initial HERMES III diode design [279] were all presented in a number of papers. Many of these designs have come to fruition at HERMES III and the reflexing diodes used at DTRA facilities.

Finally, we emphasize the importance of validating codes by comparing to experimental data. There is a long history of code validation work that was performed to ensure that the radiation transport codes used to predict the radiation output of facilities or dose in devices could be used with confidence. A number of important papers compared data from carefully controlled experiments to code predictions to check code accuracy for bremsstrahlung and secondary electron production as a function of energy, angle, and attenuation [102], [104], [105], [106], [115], [275]. The importance of equilibration and following secondary electron transport for range thin materials were key features in these papers.

VI. CONCLUSION

In the 40 year history of the IEEE Nuclear and Space Radiation Effects Conference the "Dosimetry and Facilities Session" has covered a wide variety of subjects, ranging from dosimetry development and radiation transport to dose enhancement and radiation effects test facilities. Of special note we emphasize that the session title has not captured the session's wealth of basic physics information in the areas of electron/photon radiation transport, neutron dosimetry and testing issues, radiation transport code development and their applications, and in understanding the myriad difficulties involved in conducting good experiments. Finally, this session has been a good place to find out about how to conduct good experiments and what facilities and dosimetry tools are available.

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