NBS TECHNICAL NOTE 1119

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

A Thermoluminescence Dosimetry System for Use in a Survey of High-Energy Bremsstrahlung Dosimetry

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A Thermoluminescence Dosimetry System for Use in a Survey of High-Energy Bremsstrahlung Dosimetry

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A Thermoluminescence Dosimetry System for Use in a Survey of High-Energy Bremsstrahlung Dosimetry

Margarete Ehrlich and Christopher G. Soares

This is the final report covering the work performed under an interagency agreement between the National Bureau of Standards and the Bureau of Radiological Health during the fiscal years 1978 and 1979. A thermoluminescence dosimetry system suited for a survey of high-energy bremsstrahlung in U. S. radiation-therapy departments was selected and calibrated. The experiments leading to the choice of the recommended operational characteristics, including dosimeter handling, annealing and readout, dosimeter stability in the contemplated mode of operation, dosimeter response over the photon-energy range to be covered, irradiation geometry and irradiation level are treated in detail. Results are reported of a pilot study involving the shipment of a typical survey assembly (a plastic phantom loaded with a set of dosimeters) for irradiation in one U. S. therapy department and the overall uncertainty of the proposed survey procedure is discussed.

Key words: Calibration; dosimetry; high-energy bremsstrahlung; operational characteristics; radiation therapy; recommendations; selection of thermoluminescence dosimetry system; survey; thermoluminescence; United States.

1. HISTORICAL REVIEW OF WORK PERFORMED

In early June 1977, the Bureau of Radiological Health, Division of Electronic Products (BRH), started negotiating with the National Bureau of Standards, Center for Radiation Research (NBS), the establishment of a contract to design, evaluate and calibrate a mailable dosimeter system suited for a survey of the dosimetry in bremsstrahlung beams used in the United States' radiation-therapy departments. It was agreed that, initially, beams with maximum bremsstrahlung energies between 4 and 10 MeV were to be considered and that, if possible, the survey system was to be similar to the one used by the BRH for other ongoing dosimetry surveys. The system was to be capable of dose interpretation with an uncertainty of less than 5 percent.

In anticipation of the formal Interagency Agreement for this work, NBS proceeded with the procurement of a hot-nitrogen thermoluminescence dosimetry (TLD) reader (Harshaw Model 2000D)* similar to the readers employed by BRH

*Commercial product identification does not imply a recommendation or endorsement by NBS, nor does it imply that NBS considers the identified products to be the best available for the purpose.

and with studies (a) to ascertain whether there existed a commercially available thermoluminescence (TL) material with fewer drawbacks than the LiF (TLD-100) material now in use by BRH; and (b) to determine whether it would be feasible to dispense with furnace annealing of the dosimeters between use cycles. These studies were started prior to the installation of the hot-nitrogen reader which was ordered in June 1977 and arrived in February 1978, and were then continued and concluded after reader installation. Based on the results of these studies,(1) we concluded that industry had not as yet solved all the problems with hygroscopy and fading of $Li_2B_4O_7$(Mn) which otherwise has certain advantages over LiF as a thermoluminescence phosphor. Therefore, we agreed to focus all further work on LiF (TLD-100) which is in use at BRH for several other surveys.

At the time the Interagency Agreement was formally established (May 1978), we were in the process of devising a semi-automated data-collection and handling system, of carrying out a long-term fading study and of deciding on the phantom types to construct for future tests. A few months later, during the annual summer meeting of the AAPM, an information exchange between the AAPM Therapy Committee, BRH and NBS took place. NBS had suggested this meeting in order to ensure that the AAPM Therapy Committee was informed at an early planning stage of the survey envisaged by BRH. As a result of the information exchange, the chairman of the Therapy Committee assigned a liaison committee under N. Suntharalingam's chairmanship to assist with technical and administrative problems that might arise in connection with the NBS project and the subsequent BRH survey. The liaison committee met with interested BRH and NBS staff members in Washington in October 1978 and made valuable technical suggestions. It was decided that, in the future, the liaison committee would be apprised of major developments mainly by informal telephone conversations and also would be sent copies of major reports and papers on the subject.

During the last four months of the initial year of the Interagency Agreement, the tests of a water and a Lucite phantom were completed. Based on the results of this study and following the suggestions of the AAPM liaison committee, it was decided to do all further work with the Lucite phantom which, although resulting in a more expensive mailing kit, would give a higher degree of reproducibility than a mailing kit similar to that used by the IAEA.(2) (Note that the IAEA holder is loaded with dosimeters by the participants, who then insert it into their own water vat.) During this same period, the data-processing system was essentially completed and immediately put to use in the evaluation of a large body of information that had accumulated on the reproducibility of dose interpretation from dosimeter response obtained with the chosen system under controlled conditions both with batch-type and with individual dosimeter calibration. This study was completed early during the second year of the Interagency Agreement and led to a decision on the minimum number of dosimeters required per data point for obtaining the desired accuracy level for the dosimetry survey.* Also, mainly because of the uncertainties added in each additional calibration step, NBS suggested that BRH eliminate the intermediate step of a 100-keV bremsstrahlung calibration from their survey plans.

During the first months of the second year of the Interagency Agreement, studies were completed also on minimum phantom size and on the feasibility of irradiating dosimeters simultaneously at several phantom depths. Then, in March 1979, a pilot study involving only one participant was initiated. The selected phantom, loaded at four depths with the minimum number of required dosimeters, was shipped to Massachusetts General Hospital for irradiation with 10-MV bremsstrahlung and returned to NBS for an evaluation of dosimeter response (TL signal) in terms of cobalt-60 absorbed dose to water, using most of the correction and calibration factors to be employed in the final survey (i.e., the corrections for individual dosimeter response and for fading and the cobalt-60 absorbed-dose calibration factor). A report on this and other studies carried out under this Agreement was included in a paper presented in late March, 1979 at the IAEA meeting of the Advisory Group on High Energy Photon and Electron Dosimetry. The report is contained in a paper that will be published in an IAEA document on the proceedings of this meeting. A copy of the preprint of this paper has been made available to BRH. A copy also was made available to the chairman of the AAPM liaison committee.

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* In the summer of 1979, a report on this phase of our work was prepared after inclusion of further information gathered during our small pilot study (see second paragraph above) and consultation with the NBS Center for Statistical Engineering. The report was made available to BRH and to the chairman of the AAPM liaison committee and is encompassed by this Final Report.

In a follow-up discussion between NBS and BRH in March 1979, BRH decided that the participants would be asked to compute the dose delivered for a depth of 10 cm in water rather than for the 5-cm depth at which many of them obtain their calibrations. In April 1979, as a result of discussions at the IAEA meeting in which Robert Morton, Chief of the BRH Therapy Branch, participated, it was agreed that BRH, in their instructions to the participants, should ask them to administer to the Lucite phantom, at a depth of 10 cm, the dose computed for a depth of 10 cm in water, i.e., carry out the irradiations as if the phantom were water rather than Lucite. As a result, we decided to determine high-energy bremsstrahlung absorbed dose at a depth of 10 cm in Lucite. We also decided to carry out the main bulk of the high-energy bremsstrahlung calibrations at the 100-rad level. This removes the need for additional annealing procedures to eliminate interference from spurious signals, possibly associated with deeper, hard-to-empty electron traps.

Finally, during the summer and fall of 1979, NBS determined dosimeter response in the agreed geometry to 4-, 6-, and 10-MV clinical bremsstrahlung beams relative to that to cobalt-60 gamma radiation. The comparison at 6 MV between the absorbed-dose computation from ion-chamber response and C_λ values to that from absorbed-dose calorimetry was initiated, but so far has not been completed. During this period, NBS also assisted BRH in a calibration of the BRH batch of LiF (TLD-100) in the NBS cobalt-60 and 100-kV facilities, and -- toward the end of September 1979 -- started on the cobalt-60 gamma-ray calibration of five BRH ion chambers in terms of exposure and absorbed dose. In the following sections, the final results of the NBS studies on the selected TLD system are presented in detail and recommendations are made regarding the BRH survey procedures.

2. THE SELECTED TLD SYSTEM

Since the TLD system used for most of the studies is similar to the systems available at BRH,[3] no physical description is given here. The remarks are restricted to a description of the dosimeter handling, annealing, calibration and readout procedures.

2.1 Dosimeter Handling

The LiF (TLD-100) dosimeters were never exposed to direct sunlight or any other illumination containing a large ultraviolet component. A vacuum pickup was used for dosimeter transfer.

2.2 Annealing

Between experiments, the LiF (TLD-100) dosimeters were annealed in blocks of 100 on a stainless-steel tray shown in figure 1. Pre-irradiation annealing consisted of first placing the loaded trays for 1 hour in a 2-KW muffle furnace maintained at a temperature of $400^{\circ}C$; then allowing them to cool for 30 minutes on a Transite (asbestos) surface and subsequently placing them for 1 hour in a CENCO laboratory oven maintained at $100^{\circ}C$. After another cooling cycle on the Transite sheet, the dosimeters were ready for the next irradiation. Immediately preceding readout, the dosimeters were loaded into the Harshaw disc-type readout holders and the holders were placed in the $100^{\circ}C$ CENCO oven for another 10 minutes of heating, followed again by cooling on Transite.

2.3 Calibration Procedure

Characterization of dosimeter response (TL signal) can be done either on a batch or an individual basis. Both involve reproducible reference irradiations. For all experiments described, these irradiations were performed in a cobalt-60 gamma-ray beam with the dosimeter under an equilibrium thickness of 5 mm of Lucite. Exposures were administered for a fixed length of time (90 s), and were in the 4-to-6 R range. If dosimeter identity is maintained during this procedure, it is possible to correct the subsequent response of each dosimeter to its reference response and hence eliminate the uncertainty due to differences in sensitivity* between individual dosimeters. We performed this type of individual calibration between any two successive uses of the dosimeters. The sensitivity assigned to each dosimeter in a particular use cycle was the average of the sensitivities obtained in the preceding and the following calibration cycle.

An alternate approach is to select a batch of dosimeters such that the dosimeter sensitivity falls within a certain range of values. The average of this group of sensitivity values is then used to characterize the batch for comparisons between experiments. We found that when the histories of all dosimeters in a batch were similar, the dispersion of dosimeter sensitivities (as given by the standard deviation from the mean) reproduced well over many

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*In this Report, dosimeter response (TL signal) at a given irradiation level (or per unit of the irradiation quantity) for brevity's sake is also referred to as "sensitivity", regardless of whether the irradiation quantity is exposure or absorbed dose.

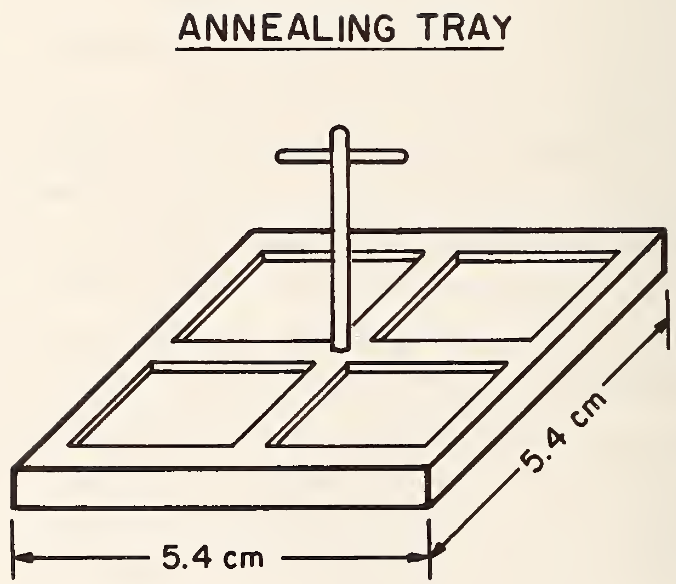

Fig. 1 Stainless-Steel Annealing Tray. Each square cutout holds 25 LiF (TLD-100) dosimeters.

use cycles. In general, the batch-calibration approach leads to less precise results, however, since, in practice, it is not feasible to select a dosimeter batch with initial sensitivities differing from each other by less than ±3 to ±5 percent and dosimeter histories are not necessarily similar, a condition that may lead to significant changes in sensitivity. (See also Section 4.7 of this Report.)

2.4 Timing of Irradiation and Readout Sequences

For most of the experiments described, irradiations were made in the afternoon, with readout the following morning, i.e., after approximately 16 to 18 hours. This allowed for extended irradiation periods (up to as much as 2 hours) without any significant difference in fading of dosimeter response between irradiation and readout.

2.5 Reader Characteristics

All readouts were performed with the hot-nitrogen reader, Harshaw Model 2000D, at a gas temperature of $300^{\circ}C$ ($\pm 10^{\circ}C$) and a nitrogen flow rate of 4.0 (±0.3) ℓ/min. This was the maximum flow rate attainable with this reader at this temperature. Some time after we had started our experiments, Harshaw modified the heater design, increasing the diameter of the gas-inlet tube to the reader chamber. This had the effect of increasing the effective heating volume and resulted in faster heating of the dosimeters and reduced dependence of dosimeter response upon dosimeter orientation and position in the gas stream. Experiments with the original heater indicated better reproducibility of responses and glow curves with the dosimeters oriented parallel to the direction of gas flow. This effect all but disappeared with the newer design and, in fact, after installation of the new heater, we determined that there was a slight enhancement in response (< 1%) with the dosimeters oriented 45° with respect to the flow direction. However, we continued to perform all readouts with the parallel orientation. Also, proper alignment of the vacuum pick-up used to raise the dosimeters into the gas flow was quite critical with the original heater design, but not nearly as critical with the later design.

Another consequence of the new heater design was an increase in photomultiplier (PMT) dark current. This is probably due to the larger heating volume and insufficient PMT cooling. However, at the irradiation levels employed, dark current was sufficiently small compared to the TL signal so that no dark-current correction was required.

One disappointing feature of the Harshaw hot-nitrogen reader was the lack of a reliable and accurate reference-light source for monitoring PMT stability. The light source furnished -- a green light-emitting diode operated at 2 V --is temperature dependent. Since the reader's temperature-stabilization system (water circulation in the block adjoining the PMT) is not sufficiently effective to prevent temperature fluctuations in the light source, the light source is essentially useless. Another difficulty resulting from the relatively poor design of the temperature-stabilization system is the easy clogging of the small water-circulation tubes. This was a continuing problem until we filtered the water supply in order to remove inorganic contaminants.

3. DATA RETRIEVAL AND HANDLING SYSTEM

Current from the PMT was fed to a fixed-scale current integrator where it was digitized for display. The analog signal was also monitored with an analog plotter for recording glow curves. The integral in digital form initially was converted to serial Ascii code for printout with a standard teletypewriter. This necessitated paper-tape storage of the data, for which retrieval for analysis is rather slow. To remedy this, an off-the-shelf microcomputer was obtained and programmed to accept and display the serial data and to store them on 5" floppy disks. This system allows compact storage of a large amount of data (from five to forty thousand readings per disk) with quick and easy retrieval for analysis. Thus only simple programs were required for such tasks as individual calibration corrections and statistical analyses. Figure 2 gives a schematic representation of the final arrangement used.

4. RESULTS OF EXPERIMENTS

4.1 Dependence of LiF (TLD-100) Sensitivity on Photon Energy in the Range from about 10 keV to about 1 MeV

Because of the relatively heavy filtration in the accelerator beams*, it is not expected that there will be an appreciable contribution of low-energy photons in the primary bremsstrahlung beam. This is borne out by the

*The 10-MV bremsstrahlung beam from a Clinac 18 is filtered with about 2 cm of tungsten, while the 4-MV bremsstrahlung beam from a Clinac 4 has a lead-antimony flattening filter of a maximum thickness of 1 cm.[4]

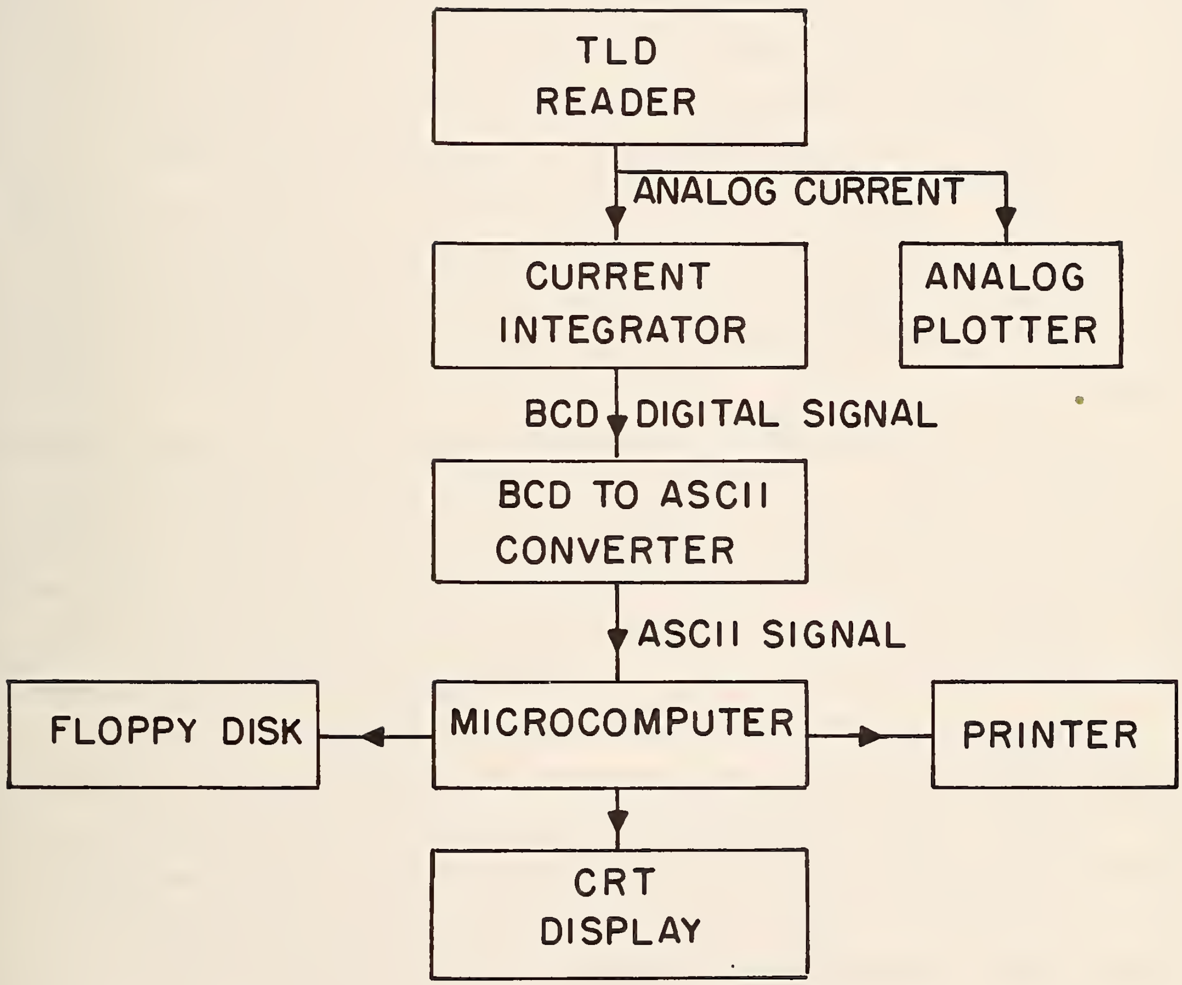

Fig.2 Schematic Representation of Data-Acquisition System

spectrometry results of L. B. Levy et al[5] who find a low-energy cutoff at about 0.4 MeV in the spectrum of the beam from an 8-MV Mevatron, having, among other filtration, a tungsten-copper flattening filter of more than 1 cm in thickness in the primary beam. However, as the beam enters the phantom, considerable buildup of a low-energy component is expected. In fact, according to the calculations first carried out by Spencer and Fano[6], a spectral peak located between 50 and 100 keV (regardless of source energy) gradually grows in importance as the depth of penetration into the phantom is increased. For the resulting photon spectra at a depth of 10 or 15 cm in the phantom (15 cm of water representing over 1 mean-free path for a 1-MeV photon and about one-half of one mean-free path for a 4-MeV photon) the effect on the response of the LiF (TLD-100) of the contribution to absorbed dose from the photons in the vicinity of the low-energy peak may not be negligible, particularly for a 4-MV accelerator. (Note that, for a 1-MeV photon, the contribution to absorbed dose at a depth of 1 mean-free path amounts to about 9 percent.)

Because of the presence in the bremsstrahlung beam of a photon component in the energy region in which dosimeter response was not expected to be independent of photon energy, a study was carried out with batch-calibrated dosimeters annealed during readout in the Harshaw hot-nitrogen reader, having sensitivities lying within a ±2 percent band. The radiation spectra were those of the heavily filtered NBS low-energy standard bremsstrahlung beams[7] and of the NBS standardized cesium-137 and cobalt-60 gamma-ray sources. Identical irradiations were administered to four samples each at three different exposure levels between about 120 and 800 mR, for which supralinearity proved to be negligibly small over the range of photon energies employed. For all but the cobalt-60 and cesium-137 gamma irradiations, the samples were irradiated bare, supported on a Bakelite strip. For the cobalt-60 and cesium-137 irradiations, an electron-equilibrium layer of about 5 mm of Lucite was used over the dosimeters.

Figure 3 shows average dosimeter sensitivity (response per unit exposure) as a function of effective photon energy*, all relative to the sensitivity to cobalt-60 gamma-ray photons. There is a relatively large increase in dosimeter

*Effective energy is here defined as the energy of a monoenergetic photon beam associated with the total (narrow-beam) attenuation coefficient obtained from the attentuation curve of the photon beam in question in a suitable absorber (for example, Al or Cu), extrapolated to zero absorber thickness.

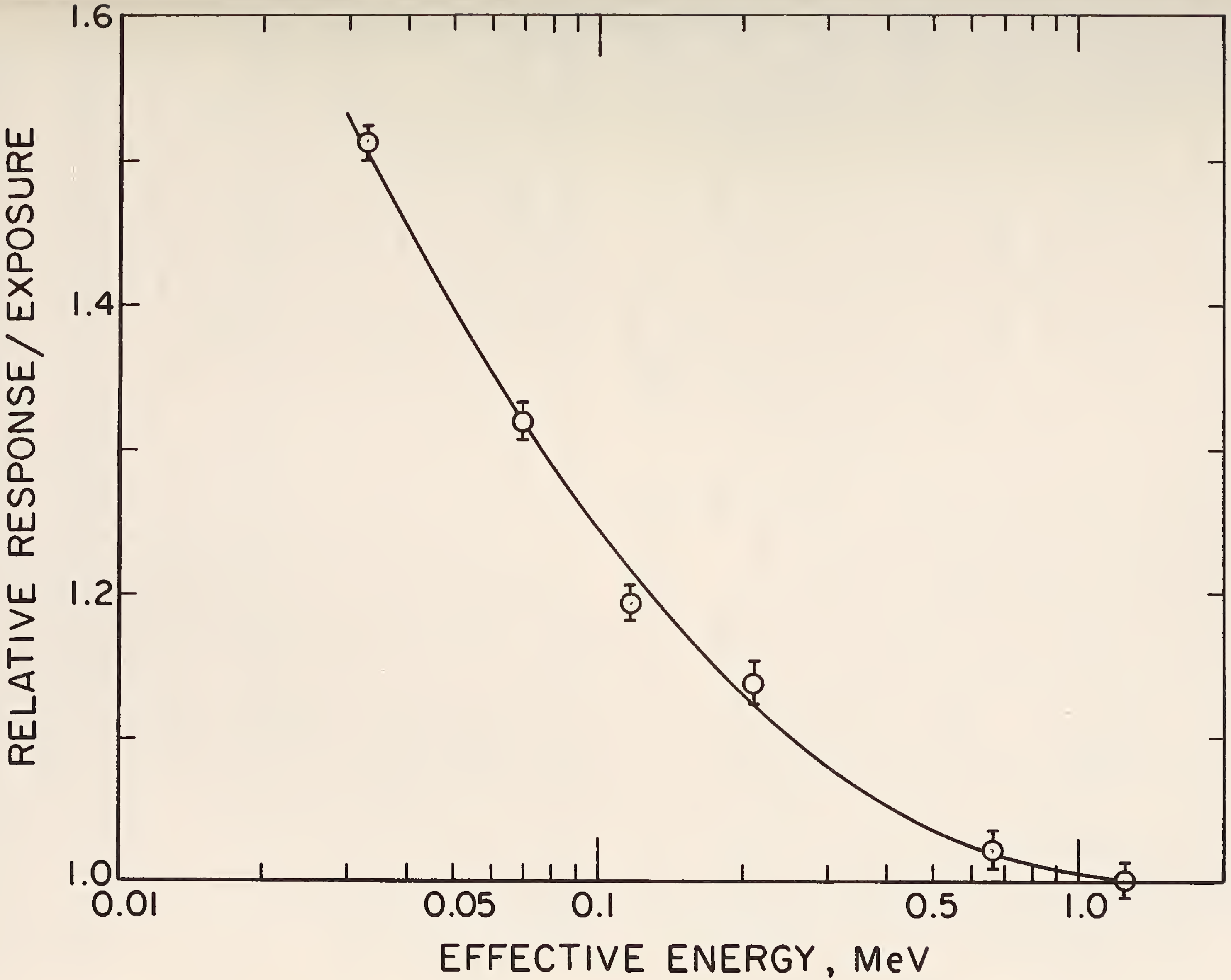

Fig. 3 Dependence of Dosimeter Sensitivity on Photon Energy in the Range from about 0.03 to 1 MeV. Response per unit of exposure is plotted relative to that for cobalt-60 gamma rays.

sensitivity at low-photon energies amounting to about 50 percent at 34 keV.*
As a result of the increase in sensitivity at low photon energies of the LiF dosimeters, the depth-dose data that will be obtained in the survey may not exactly correspond to depth-dose data as measured with ion chambers. This will be of no significance in the envisaged survey, in which the participants will be asked to deliver an absorbed dose to water at one prescribed depth in the Lucite phantom. Nevertheless, in order to investigate the limitations of the present system, we also computed response for a given irradiation level as a function of depth in water from the response as a function of depth in Lucite. The response as a function of depth in Lucite was measured by maintaining the distance between the source and the detector at 1 meter and changing the depth of the dosimeters inside the phantom. For all irradiations, the beam cross section in the plane of the dosimeters was 10 cm x 10 cm. Dosimeter readings were related to absorbed dose to water at the same location, utilizing source-standardization data derived from absorbed-dose calorimetry in the same beam for the same field size and distance. The depth in water (t_{water}) equivalent to a given depth in Lucite (t_{Lucite}) was computed as

$$t_{water} = t_{Lucite} \, (\overline{Z/A})_{Lucite} \,/\, (\overline{Z/A})_{water} \,, \tag{1}$$

where $(\overline{Z/A})$ stands for the average of the quotient of atomic number and atomic weight here taken for Lucite and water, respectively, as indicated by the subscripts. The depth, t_{water}, computed in this way is the depth at which the percent depth dose in water is the same as the percent depth dose at the depth, t_{Lucite}, in Lucite.[9] Figure 4 shows the results. The dosimeter readings were arbitrarily fitted at a depth of 5 cm, but could be fitted at any other depth, just as well. The results indicate that, at least for the spectrum emitted by the ^{60}Co gamma-ray source used for this experiment, the difference in slope of the response-versus-depth and the depth-dose curves is relatively small and results in a slight increase in response per unit of absorbed dose with increasing phantom depth (i.e., for lower photon energies).

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*This was one of the reasons why we investigated the feasibility of replacing the LiF dosimeter by a $Li_2B_4O_7$ dosimeter. Note that H. K. Pendurkar et al at C.E.N., Mol, Belgium[8], report a 50-percent higher sensitivity of LiF (both TLD-100 and microrods) for irradiation to about 30-keV photons than for irradiation with 1-MeV photons. On the other hand, they report the corresponding increase for $Li_2B_4O_7$ microrods to be less than 15 percent.

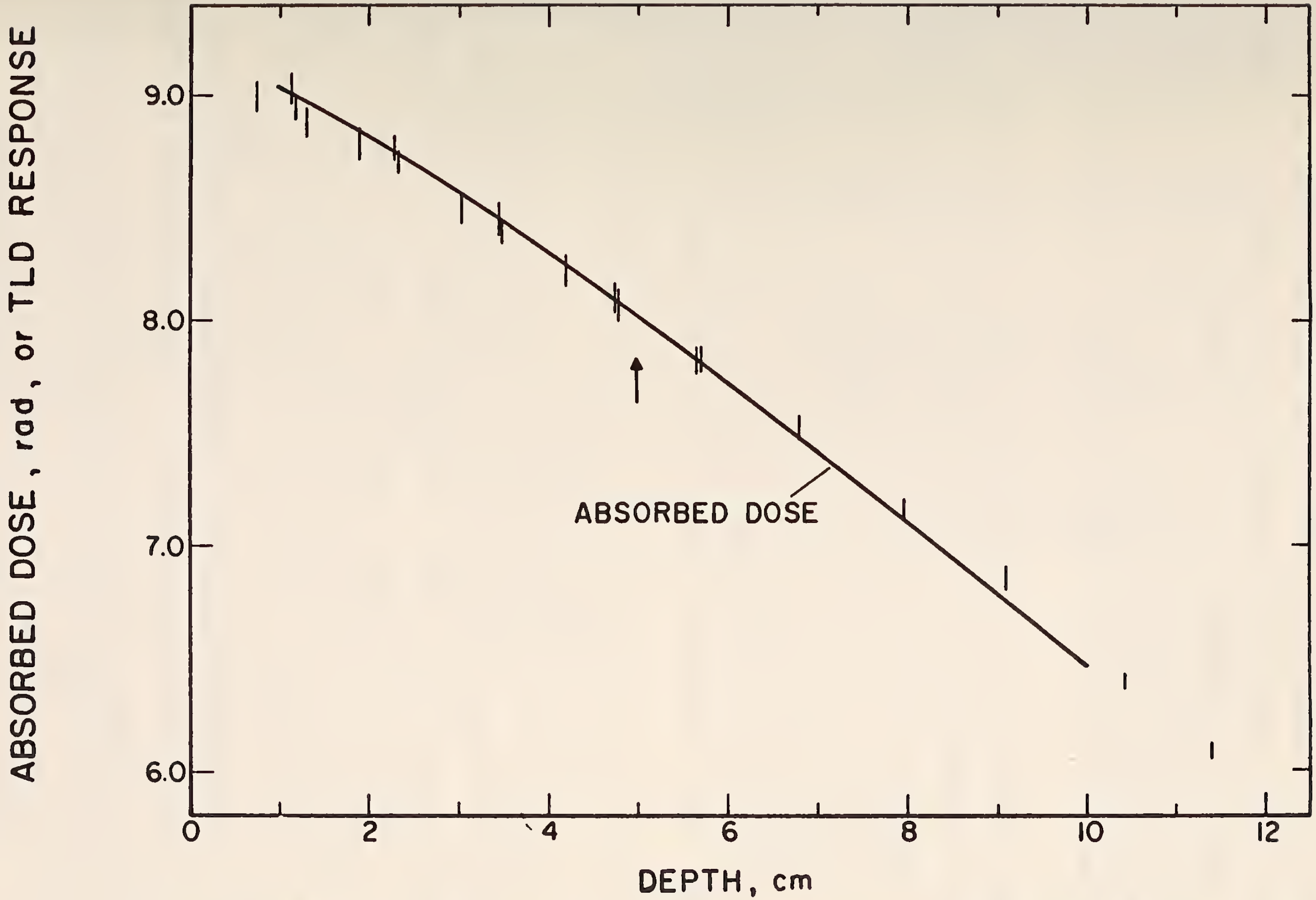

Fig. 4 Comparison, Absorbed Dose to Water and Dosimeter Response in Lucite, for Irradiation with Cobalt-60 Gamma Rays, as a Function of Depth in Water. The field size was 10 cm x 10 cm at each depth of measurement. The error bars represent the standard deviation (0.5 to 0.9%) of the response of the nine dosimeters irradiated at each depth. The solid line represents calorimetric depth-dose data in water obtained in the same geometry with the same cobalt-60 gamma-ray sources. The response curve was fitted to the absorbed-dose curve at a depth of 5 cm in water (arrow).

4.2 Fading of LiF (TLD-100) Response Under Laboratory Conditions

This experiment was carried out for storage in the dark, at temperatures between 18° and $22^{\circ}C$ and at relative humidities of less than 45 percent. Tests over a wide range of temperatures and relative humidities were not considered necessary since fading for the annealing methods employed is known to be relatively small for any ambient condition and possible effects due to variations in ambient conditions thus would be within the measurement uncertainty. Furthermore, BRH has employed the system for postal surveys for several years, without experiencing any difficulties due to variations in ambient conditions.

Figure 5 shows the results of the study, which covers storage periods between irradiation and readout in the range from about 3 to 24 days at three cobalt-60 gamma irradiation levels (10, 100 and 200 rad). The response data were arbitrarily normalized to the three-day response points. Since the amount of fading was shown not to be a function of irradiation level, a least-squares fit regression line (see formula in fig. 5) was fitted to all the data points obtained for the period from three to 24 days between irradiation and readout. Over this period, fading is seen to amount to about 2½ percent.

4.3 Influence of Size of Lucite Phantom on Dosimeter Response for the Spectra of Interest

In order to determine if it would be feasible to use for the survey a phantom smaller than the standard phantom cube with sides of 30 cm in length, a study was carried out with smaller cubes. Cubes with sides 15 cm and 20 cm in length loaded at three and four depths, respectively, were irradiated with cobalt-60 gamma radiation and with 10-MV bremsstrahlung. Figure 6 illustrates the loading of one of the phantoms. The results of the experiments are shown in table 1. Listed is the response for a fixed irradiation level averaged over the values for nine dosimeters irradiated simultaneously at the particular depths in the two phantoms and radiation beams. The field size was 10 cm x 10 cm in the plane of each measurement. The data reveal a slight trend for responses in the larger phantom to be somewhat higher than those in the smaller phantom, for irradiation with either radiation beam.* Since this trend, if significant,

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*Note that this finding agrees with earlier depth-dose measurements with ion chambers in graphite phantoms made by J. Pruitt and S. Domen of our laboratory, who found a difference of 0.7 percent at a 10-cm depth.

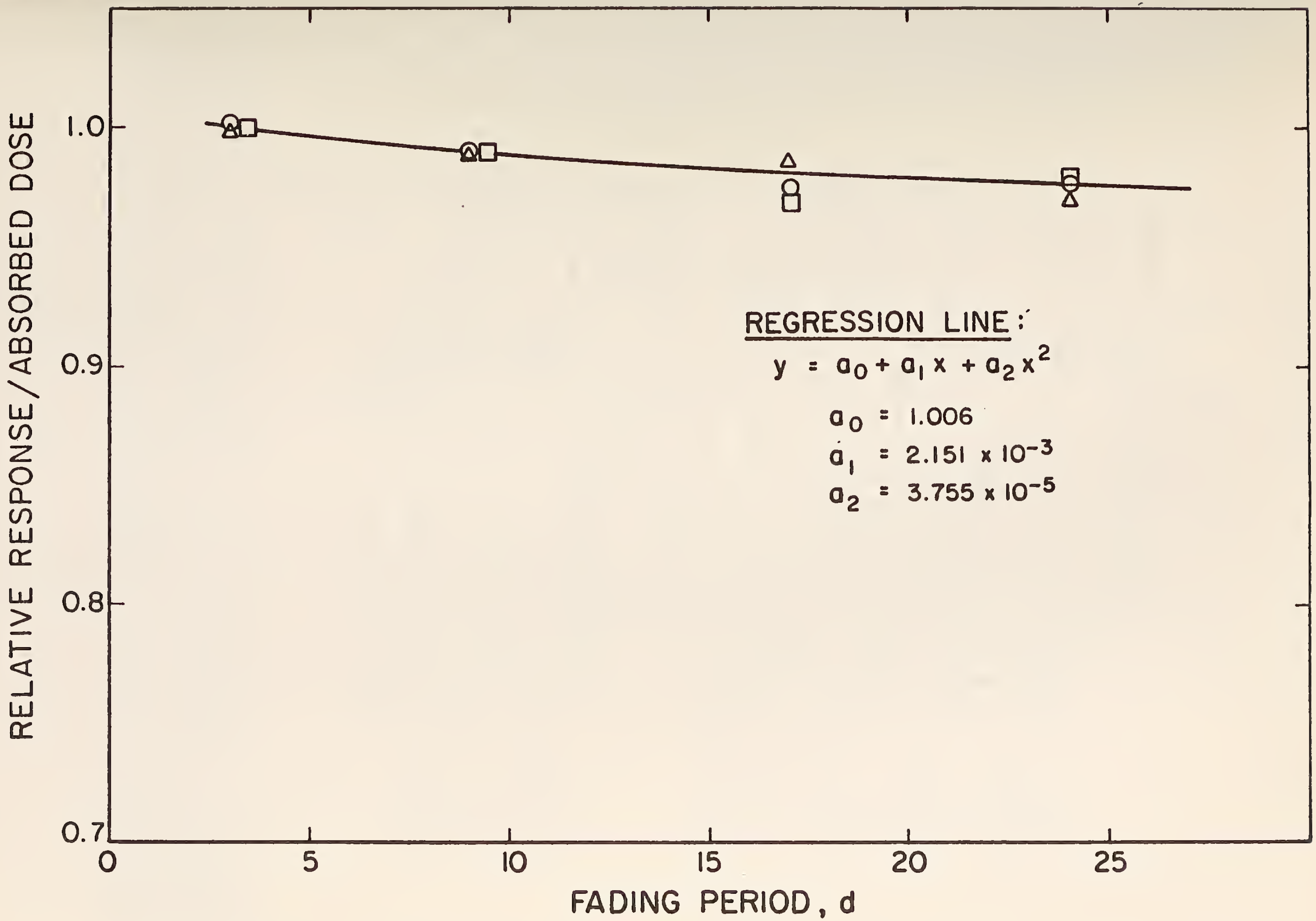

Fig. 5 Fading of Dosimeter Response for Three Different Absorbed-Dose Levels. Plotted is response per unit of absorbed dose, corrected for supralinearity. Circles: 10-rad level; Squares: 100-rad level; Triangles: 200-rad level. All data were normalized to the three-day value for the respective absorbed-dose level.

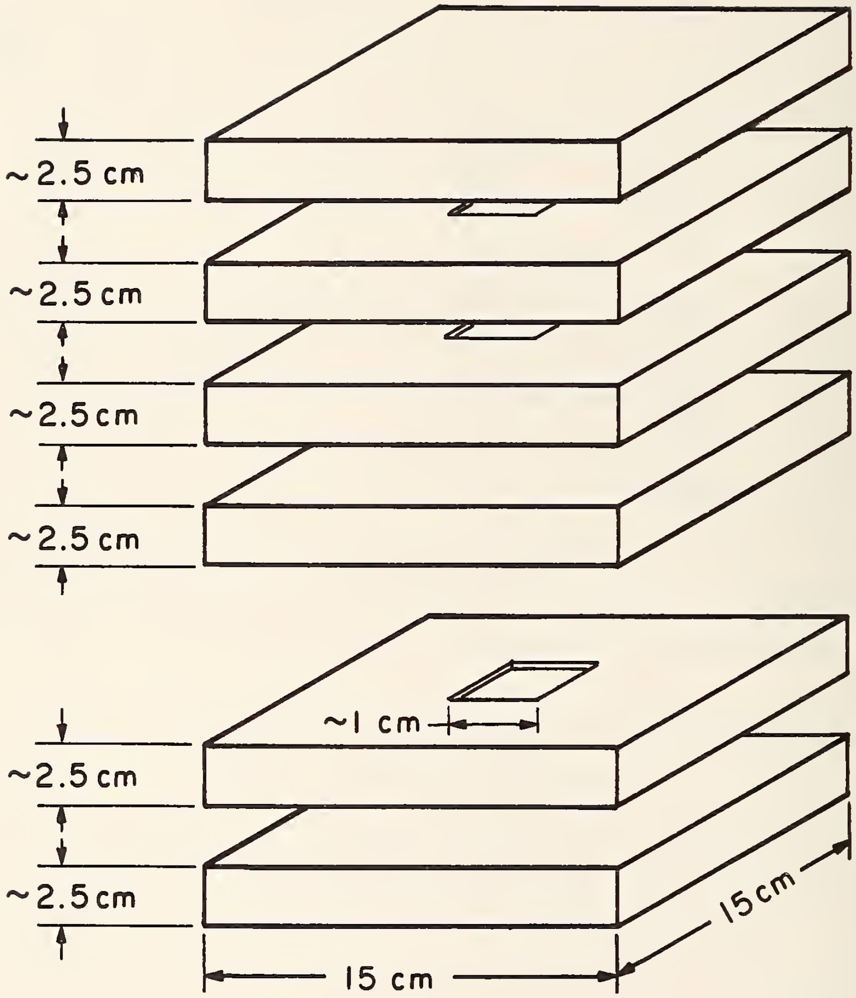

Fig. 6 Exploded View of the 15-cm x 15-cm x 15-cm Lucite Phantom. Cutouts just deep enough to accommodate on layer of dosimeters were provided for nine dosimeters at nominal depths of 2.5 cm, 5 cm and 10 cm. Larger phantoms were obtained by adding Lucite plates to all surfaces. When the phantom depth was 20 cm, a cutout at a nominal depth of 15 cm could be provided, as well. In this view, the cutouts are shown on an enlarged scale.

Table 1. Influence of Phantom Size on Dosimeter Response
Field: 10 cm x 10 cm in plane of measurement

Nominal depth in phantom cm	AVERAGE DOSIMETER RESPONSE			
	Cobalt-60 gamma rays in cubic phantom with		10-MV bremsstrahlung in cubic phantom with	
	15 cm sides	20 cm sides	15 cm sides	20 cm sides
2.5	1.001 ± 0.003	0.999 ± 0.005	0.998 ± 0.006	1.002 ± 0.008
5	0.853 ± 0.003	0.860 ± 0.002	0.896 ± 0.004	0.894 ± 0.007
10	0.591 ± 0.004	0.601 ± 0.004	0.682 ± 0.004	0.685 ± 0.005
15	———	0.404 ± 0.002	———	0.522 ± 0.003

would be negligible in the envisaged survey, we decided to dispense with tests employing a phantom cube with 30-cm side length and tests employing 4- and 6-MV bremsstrahlung and concluded that it would be safe to use a phantom cube with sides 15 cm in length for the survey.

4.4 Influence on LiF (TLD-100) Response at a Given Phantom Depth in the Presence of Dosimeters in Several Other Depths

BRH had expressed an interest in designing the survey in such a way as to obtain some information on depth-dose data from the various participating institutions. If possible, this information should be obtained from the results of one single irradiation of the phantom, loaded with dosimeters at different depths along the central phantom axis. In order to ascertain the feasibility of such a procedure, we investigated whether simultaneous phantom loading at different depths influences dosimeter response to the different radiation beams under consideration. Table 2 gives the results of this investigation. Shown is average response of nine dosimeters at a nominal depth of 10 cm in the phantom, in the presence and in the absence of dosimeters at other depths, and the relative standard deviations of these averages. Because of a BRH decision to use phantom cubes with 20-cm sides in their survey, we did not obtain data with all types of radiation for the other phantom sizes.

The data shown in the table reveal a slight trend of questionable significance (i.e., a trend within the limits of the reproducibility of the experiment) for the presence of dosimeters at other depths to decrease the response of the dosimeters at the 10-cm depth -- at least for cobalt-60 gamma radiation and 4-MV bremsstrahlung. Nevertheless, it is safe to conclude that the BRH plan to load the mailing phantoms in several depths beyond the peak of the depth-dose curve is entirely feasible. In fact, the work reported in Sections 4.5 and 4.6 of this Report was performed in a cubic phantom with 20-cm sides, loaded with dosimeters at nominal depths of 2.5 cm, 5 cm, 10 cm and 15 cm. The field size was 10 cm x 10 cm at a depth of 10 cm.

4.5 LiF (TLD-100) Response at a 10-cm Depth in the Lucite Phantom for Irradiation with Cobalt-60 Gamma Radiation and with High-Energy and Low-Energy Bremsstrahlung

The irradiations were performed with the NBS standardized cobalt-60 gamma-ray source and with 100-kV bremsstrahlung, the latter because BRH had initially intended to use 100-kV bremsstrahlung for their day-to-day calibrations. Irradiations with high-energy bremsstrahlung were done with accelerators both at the Radiation Oncology Department of the National Cancer Institute

Table 2. Influence on Dosimeter Response of the Presence of Dosimeters in Other Depths

TYPE OF RADIATION	AVERAGE DOSIMETER RESPONSE FOR DOSIMETERS AT A 10-cm DEPTH IN					
	Cube, 15 cm sides, with dosimeters at		Cube, 20 cm sides with dosimeters at		Parallelepiped, 15 cm x 15 cm x 20 cm deep with dosimeters at	
	10-cm depth only	2.5-, 5- and 10-cm depths	10-cm depth only	2.5-, 5-, 10- and 15-cm depths	10-cm depth only	2.5-, 5-, 10- and 15-cm depths
Cobalt-60 gamma rad.	0.581 ± 0.002	0.578 ± 0.004	0.589 ± 0.003	0.588 ± 0.004	—	—
4 MV bremsstr.	—	—	0.607 ± 0.003	0.601 ± 0.004	—	—
6 MV bremsstr.	—	—	0.552 ± 0.003	0.552 ± 0.003	—	—
10 MV bremsstr.	0.681 ± 0.003	0.680 ± 0.004	0.685 ± 0.004	0.683 ± 0.005	0.683 ± 0.004	0.685 ± 0.003

and at the Radiation Therapy Department of George Washington University Hospital. At the National Cancer Institute, the two Siemens Mevatrons were used at 6 MV and one of them also at 10 MV after its conversion to a Mevatron-XII. At George Washington University Hospital, we used the Clinac-4 and the Clinac-18, at 4 MV and 10 MV, respectively. The source-to-detector distance was 100 cm for all but the 4-MV high-energy bremsstrahlung beam, where it was 80 cm.

Absorbed dose for the high-energy bremsstrahlung irradiations was obtained by determining initially the reading of a NBS-calibrated Farmer chamber and later the reading of a special NBS graphite chamber at a 10-cm depth in a water phantom cube with sides 30 cm in length and converting the reading to absorbed dose to water by multiplying with the appropriate C_λ factor as given in ICRU Report 24[10], where it is designated by the symbol F. (The factor is 0.94 for 4 and 6 MV and 0.93 for 10 MV.) At 6 MV, the absorbed dose obtained in this way also was compared with the absorbed-dose value deduced from calorimetry in graphite via readings of the NBS graphite ion chamber in the water phantom, for future direct conversion to absorbed dose to water. For the cobalt-60 irradiations, absorbed dose to water was obtained by using results from earlier measurements at the same location with the standard graphite calorimeter.

4.5.1 <u>LiF (TLD-100) response as a function of irradiation level</u>. Figure 7 shows typical data obtained for the average response of sets of nine dosimeters irradiated with high-energy bremsstrahlung and with cobalt-60 gamma radiation at a nominal depth of 10 cm, as a function of absorbed dose to water at the same depth. Dosimeter response is seen to be supralinear, even at relatively low dose levels. Quantitatively, this supralinearity is shown better in figure 8, where response/absorbed dose (sensitivity) is plotted as a function of absorbed dose, normalized for all irradiation conditions at the zero absorbed-dose level. Sensitivity is seen to increase essentially linearly with absorbed dose, the increase amounting to about 4 percent of the initial sensitivity at the 100-rad level. The difference in the slope of the regression lines obtained by least-squares fitting for the different photon spectra is only marginally significant since, in addition to the uncertainty in the fits indicated in figure 8 one must consider an experimental uncertainty

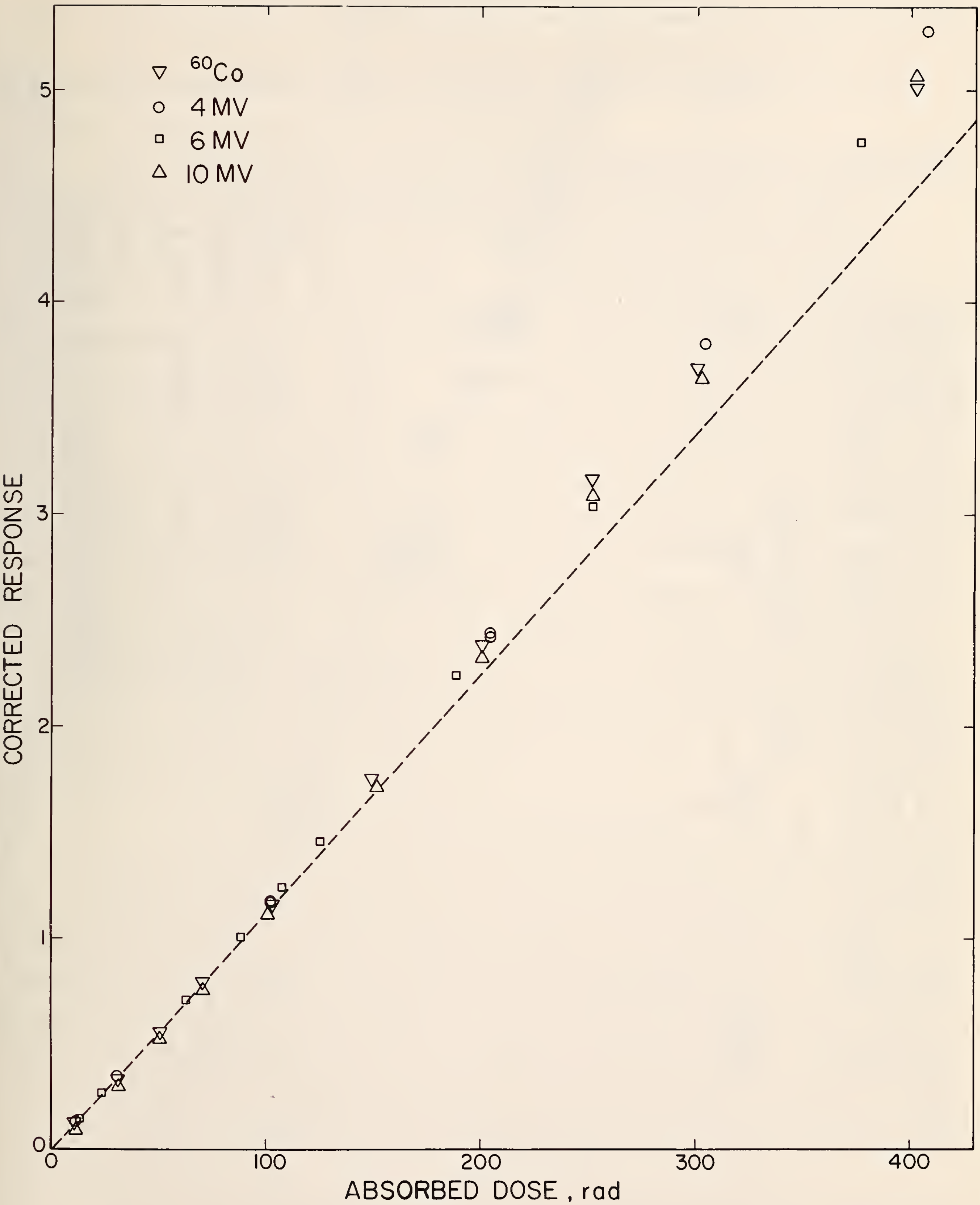

Fig. 7 Typical Dosimeter Response as a Function of Absorbed Dose. Dashed line - linear relationship between response and absorbed dose.

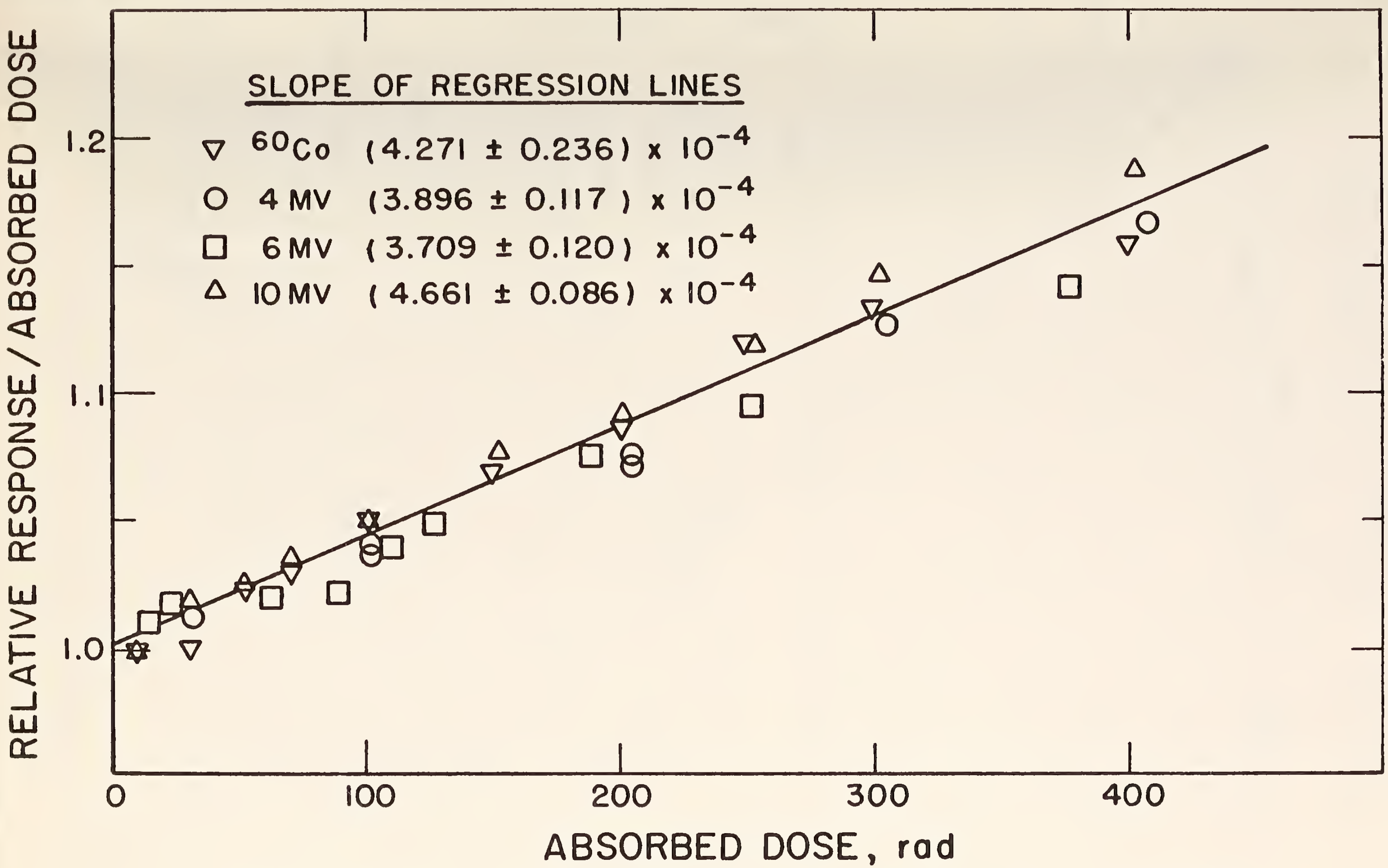

Fig. 8 Increase in Dosimeter Sensitivity with Irradiation Level for Irradiation with Cobalt-60 Gamma Radiation and High-Energy Bremsstrahlung. The regression line drawn is for cobalt-60 gamma radiation. The points for the 4-, 6- and 10-MV bremsstrahlung are shown relative to the cobalt-60 gamma-ray regression line, which was made to approach unity as absorbed dose approaches zero.

of at least 1 percent.* As a consequence, no supralinearity correction is required for a comparison between high-energy bremsstrahlung response of the dosimeters and response to cobalt-60 gamma radiation, at least not at irradiation levels in the vicinity of 100 rad.

4.5.2 LiF (TLD-100) response at a given irradiation level to high-energy bremsstrahlung relative to that to cobalt-60 gamma radiation. Table 3 shows two series of values for the quotient, Q_{Co}^{E}, which is defined as (dosimeter response in Lucite to high-energy bremsstrahlung) / (dosimeter response in Lucite to cobalt-60 gamma radiation for identical levels of absorbed-dose to water). The first series is based on experiments performed over a period of several months. For the high-energy bremsstrahlung, absorbed dose to water at a 10-cm depth in a water phantom was determined from readings of Farmer ionization chambers, with a random reading uncertainty of about 0.3 percent. The irradiations for the second series were all completed within a period of two days and all readouts were done in one sitting. For the high-energy bremsstrahlung, absorbed dose to water was determined from readings of a special NBS graphite ionization chamber, with a random reading uncertainty of about 0.1 percent. Just as could be expected from earlier studies with various configurations of LiF TLD material,[13] no significant trend is observed as a function of initial beam energy and the difference from unity of any one of the quotients is within the total uncertainty of ∿2 percent. (See uncertainty given for Q_{Co}^{E} in table 6.)

4.6 Relative Depth Dose in Lucite Phantom Derived from LiF (TLD-100) Response

Figure 9 shows representative depth-dose data for depths of 2.5 cm, 5 cm, 10 cm and 15 cm in Lucite obtained in the study described in Section 4.5. Inasmuch as the participants in the BRH survey will be asked to determine absorbed dose to water at a depth of 10 cm in the phantom, all data are plotted relative to the dose at this depth. Also, in order to facilitate the use of these results, the coefficients of the least-squares fits of all the depth-dose data obtained (including those plotted in fig. 9) are shown in table 4. These coefficients have attached to them an uncertainty of about 1½ percent beyond the

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*It is not too surprising that the difference is not large, even in the light of the known dependence of supralinearity on LET[11,12] since it may be expected that at the 10-cm depth at which the dosimeters were irradiated, the spectra had become much more similar. See also Section 4.1 of this Report.

Table 3. Quotient, Dosimeter Response in Lucite per Unit of Absorbed Dose to Water at a 10-cm Depth in the Lucite Phantom

Radiation Source	Nominal Peak Energy	Quotient[c]	
		Series 1	Series 2
Varian Clinac-4 (George Washington U. Hosp.)	4 MeV	1.01^2	0.99^1
Siemens Mevatron VI[a] (National Cancer Institute)	6 MeV	1.02^2	—
Siemens Mevatron VI (National Cancer Institute)	6 MeV	1.01^3	1.00^1
Varian Clinac-18 (George Washington U. Hosp.)	10 MeV	0.99^4	0.97^9
Siemens Mevatron XII[b] (National Cancer Institute)	10 MeV	0.97^7	1.00^0
	Average:	$1.004 \begin{smallmatrix}+0.019\\-0.027\end{smallmatrix}$	$0.993 \begin{smallmatrix}+0.008\\-0.014\end{smallmatrix}$

(a) Before conversion to Mevatron XII (see 10-MeV points obtained at the National Cancer Institute).

(b) After conversion from Mevatron VI.

(c) See Section 6 for the computation of the total uncertainty in this quotient.

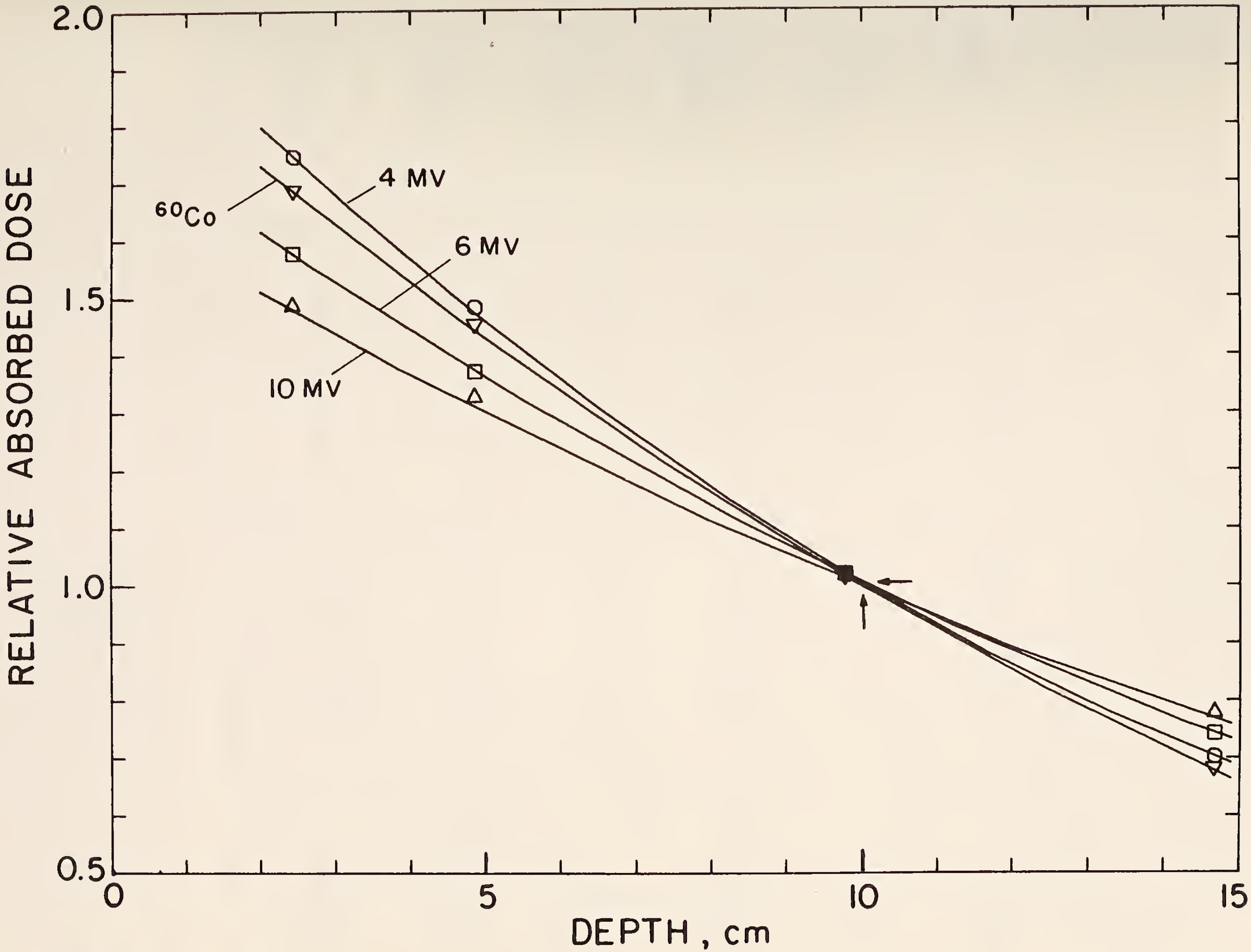

Fig. 9 Absorbed Dose to Water as a Function of Depth in the Lucite Phantom, Computed from Dosimeter Response. The absorbed dose data were normalized to those obtained at a depth of 10 cm in Lucite (arrows).

Table 4. Regression Lines, Dose Interpretation from Dosimeter Response in Lucite as a Function of Depth in the Lucite Phantom[a]

$$y = a_0 + a_1 x + a_2 x^2$$

Type of Radiation	a_0	a_1	a_2
Cobalt-60 Gamma Radiation	1.887 ± 0.004	-0.103 ± 0.001	0.00147 ±0.00007
4-MV bremsstr. (Clinac 4)	1.973 ± 0.006	-0.121 ± 0.002	0.00232 ±0.00010
6-MV bremsstr.[b] (Mevatron VI)	1.747 ± 0.005	-0.088 ± 0.001	0.00136 ±0.00008
6-MV bremsstr. (Mevatron VI)	1.785 ± 0.008	-0.095 ± 0.002	0.00164 ±0.00013
10-MV bremsstr.[c] (Mevatron XII)	1.615 ± 0.006	-0.071 ± 0.002	0.00093 ±0.00010
10-MV bremsstr. (Clinac 18)	1.635 ± 0.004	-0.074 ± 0.001	0.00109 ±0.00007

(a) Absorbed dose was set equal to unity at a depth of 10 cm in Lucite.

(b) Before conversion to Mevatron XII.

(c) After conversion from Mevatron VI.

uncertainty indicated in the table. This means that the differences between the curves obtained at any one nominal bremsstrahlung energy are not significant. On the other hand, the fitting parameters for the curves obtained at the different nominal bremsstrahlung energies show that these curves are significantly different. As a consequence, one must conclude that the method may be sufficiently accurate for obtaining some information on a participant's gross beam energy from survey data at three or four different phantom depths, but that it will be difficult to detect small differences among linear accelerators of the same nominal energy. It may be noted that plotted relative to the dose at a depth of 10 cm, the curves obtained for the NBS cobalt-60 gamma-ray beam* and for the 4-MV bremsstrahlung beam cannot be distinguished from each other. This agrees with results we obtained from depth-dose curves measured by others.**

4.7 Dependence of LiF (TLD-100) Sensitivity on Irradiation History

The experiments described so far in Section 4 were all carried out with the same set of 100 dosimeters. During these experiments, we observed that dosimeter response to the constant test irradiations of ∿5 R of cobalt-60 gamma radiation decreased monotonically with dosimeter use at the test-irradiation levels. When an experiment involving irradiation levels of ∿100 rad or more was carried out between any two test irradiations, this pattern was interrupted, the glow curves for the test irradiations following the experiment reflecting electron release from traps deeper than those filled at the lower irradiation levels, a release that tended to disappear only after several annealing and use cycles. Figure 10 shows the resulting behavior of the 100 dosimeters throughout 35 irradiation and annealing cycles. The data points indicate the average response of these dosimeters to the constant test irradiation. Where experiments involving the irradiation of some of the dosimeters followed by readout and annealing of all the dosimeters were performed between any two test irradiations, the types and levels of the intervening irradiations are indicated.

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*For the spectrum of the cobalt-60 source employed, see Ehrlich et al[14].

**While the percent depth dose at a 10-cm depth is around 4 ± 0.5 percent lower for cobalt-60 gamma radiation than for the 4-MV bremsstrahlung,[15] the depth doses relative to the depth dose at a 10-cm depth agree with each other to within 1½ percent over the range of depths from about 3 to at least 12 cm in water.

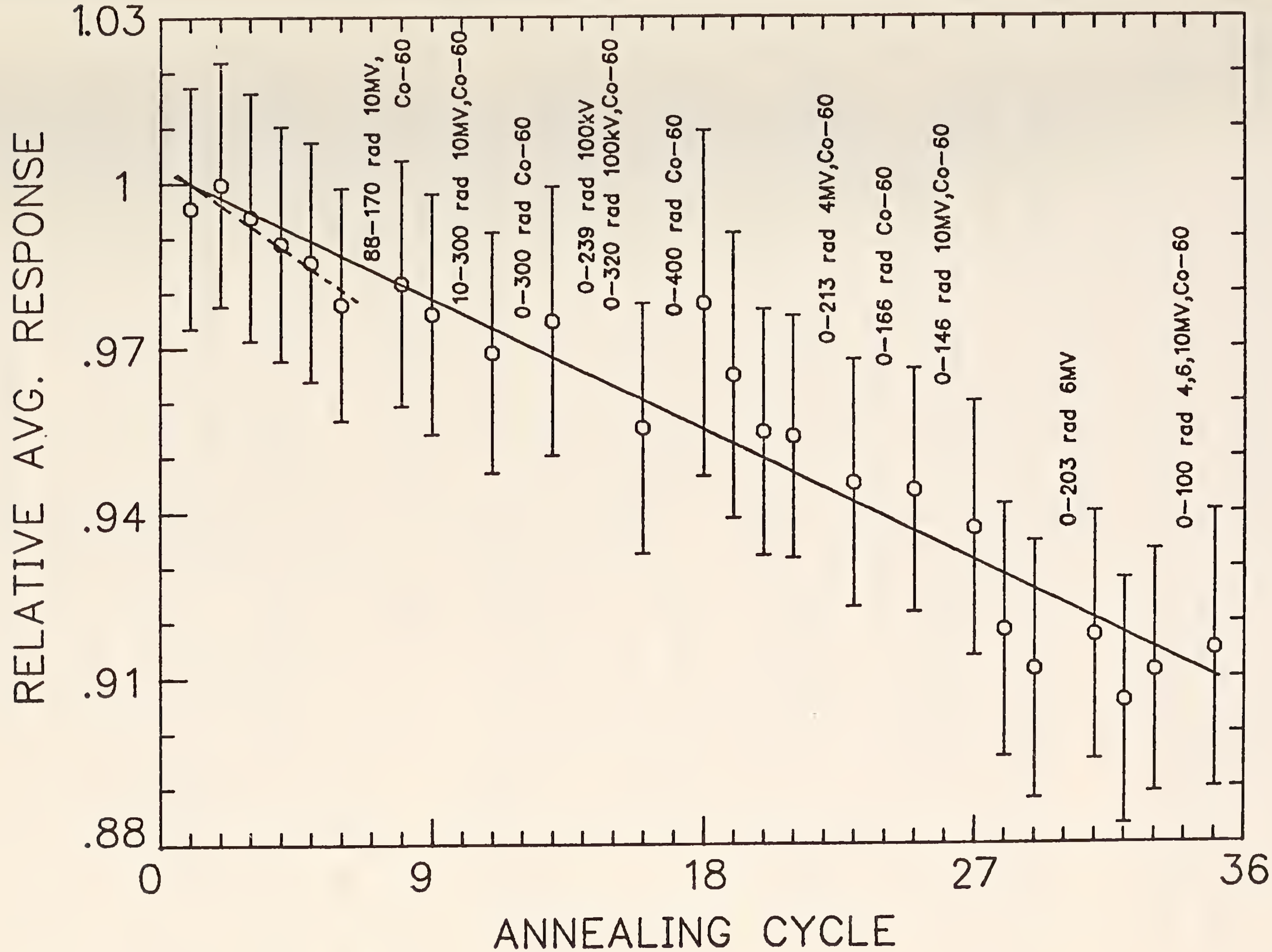

Fig. 10 Change in Dosimeter Sensitivity with Irradiation History. Average response of 100 dosimeters to a constant test irradiation is plotted. Types and levels of intervening irradiations on some of these dosimeters are indicated.

The solid straight line represents a least-squares fit to the test-data points, indicating an overall loss in dosimeter sensitivity of $\sim$9 percent after the 35 irradiation and annealing cycles. The dashed line is a fit to the first six data points for test cycles done in succession without intervening experiment runs. The decrease in sensitivity is seen to be larger, amounting to almost 2 percent after these six cycles, i.e., to $\sim$0.3 percent per test cycle.

In order to study the behavior of the dosimeters after irradiation at levels higher than the $\sim$5-R test level, the change in the response to the test irradiation is plotted in figure 11 for the average readings on a group of nine dosimeters irradiated simultaneously. The points again are for the response to the test irradiations. Where experiment cycles were interspersed, the irradiation types and levels are indicated. Note that a 400-rad irradiation causes a sensitivity increase of $\sim$8 percent, followed by a decrease in sensitivity of $\sim$3 percent per subsequent test cycle. At the 100-rad level, the increase, on the average, just offsets the decrease expected for any two successive test irradiations.

5. RESULTS OF PILOT COMPARISON STUDY

The Radiation Physics Department of the Massachusetts General Hospital (MGH) was selected for this pilot study because it had been a participant a few weeks earlier in an IAEA pilot comparison study with the Harvard School of Medicine. (This study also is covered in the IAEA report on the proceedings of the March 1979 meeting referred to in Section 1 of this Report.) At the time of the NBS-MGH study, the decision had not been made as yet to ask for delivery of 100 rad to water at a 10-cm depth in Lucite. For the NBS-MGH study, we asked MGH to administer to our phantom (a Lucite cube with 20-cm side length, loaded with 9 dosimeters each in the depths of 2.5 cm, 5 cm, 10 cm, and 15 cm) an absorbed dose from their 10-MV bremsstrahlung beam (Clinac-18) corresponding to 200 rad to water. The dose was to be delivered at a depth in Lucite of 5 cm, using a 10 cm x 10 cm field size at this depth. We computed the absorbed dose to water from a cobalt-60 source that corresponded to the response in Lucite measured with the dosimeters that had been irradiated at MGH in the 10-MV bremsstrahlung beam. We arrived at the absorbed dose to Lucite (D_{Lucite}) from the absorbed dose to water as measured by the NBS standard

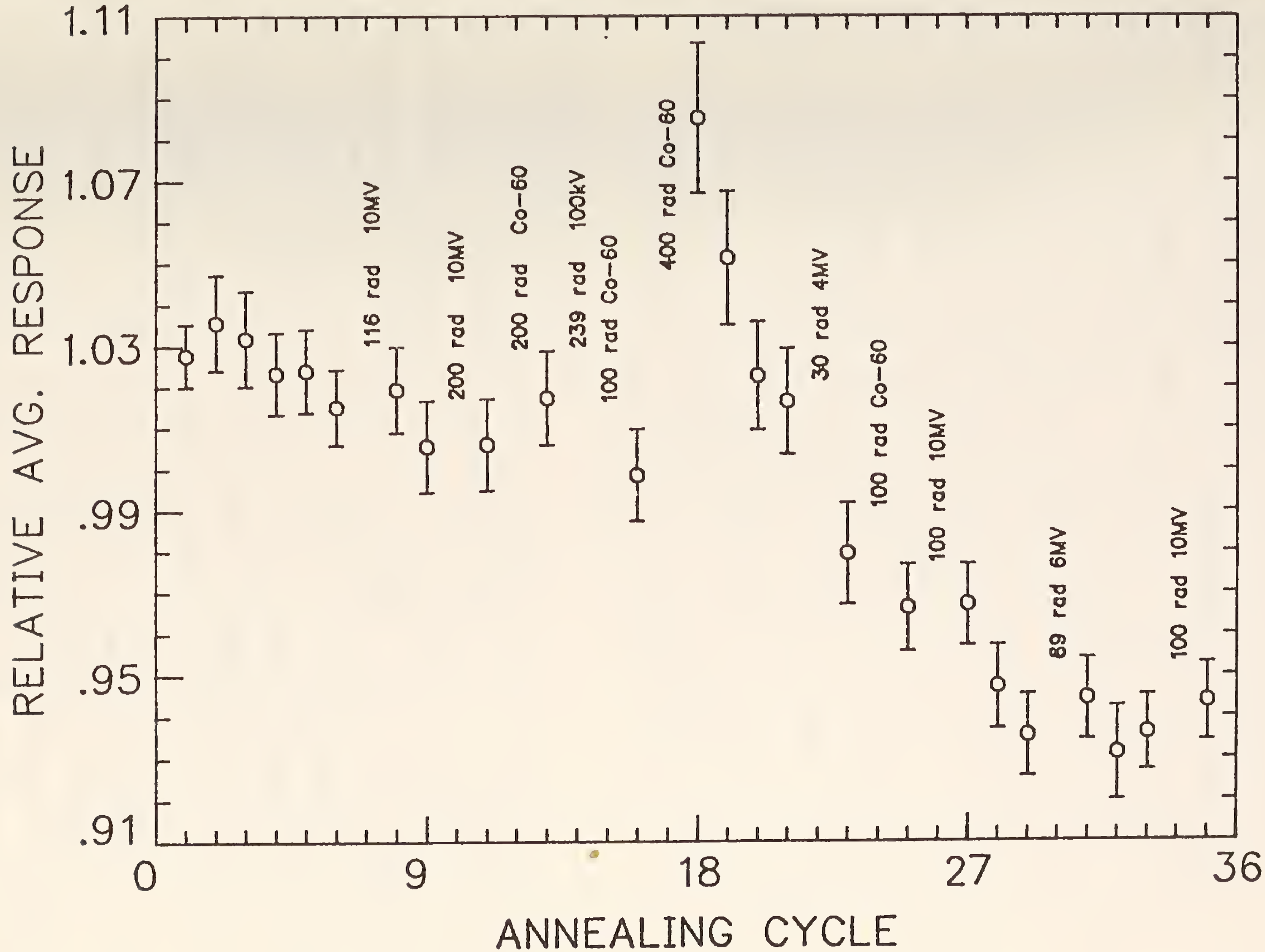

Fig. 11 Change in Dosimeter Sensitivity with Irradiation History. Average response of 9 dosimeters to a constant test irradiation is plotted. Types and levels of intervening identical irradiation on all 9 dosimeters are indicated.

absorbed-dose calorimeter as

$$D_{\text{Lucite}} \left[\mu_o(\text{Lucite})\ t_{\text{Lucite}}\right] = D_{\text{water}} \left[\mu_o(\text{water})\ t_{\text{water}}\right] \bar{\mu}_{\text{en}}{}_{\text{water}}^{\text{Lucite}} \quad (2)$$

where the μ_o symbols stand for the mass attenuation coefficients for the incident spectrum for Lucite and water; $\bar{\mu}_{\text{en}}{}_{\text{water}}^{\text{Lucite}}$ is the quotient of the average mass energy absorption coefficient for Lucite and for water, taken at a depth in water, t_{water} = 5 cm, and the corresponding depth, t_{Lucite}, computed by eq (1). Since, for our cobalt-60 gamma-radiation source, 5 cm of a low-Z material represents only a fraction of one mean-free path and μ_{en} is essentially constant over the energy range represented, μ_{en} values for the incident beam were used in the computation of $\bar{\mu}_{\text{en}}{}_{\text{water}}^{\text{Lucite}}$.

A similar computation was performed for the 10-MV bremsstrahlung beam. Equation (2) was again used to determine the relationship between absorbed dose to Lucite at a 5-cm depth in Lucite and absorbed dose to water at the corresponding depth in water. However, since $\mu_{\text{en}}{}_{\text{water}}^{\text{Lucite}}$ changes by about 2 to 3 percent between 1 and 10 MeV, an average value, $\bar{\mu}_{\text{en}}{}_{\text{water}}^{\text{Lucite}}$, was computed under the assumption of a triangular bremsstrahlung spectral distribution filtered by 1.9 cm of tungsten, which, according to Varian Associates, is the filtration in a 10-MV Clinac-18 beam.[4] The resulting value for the interpretation of the dosimeter readings in Lucite at 10 MV in terms of cobalt-60 gamma-ray absorbed dose to water was 199.6 rad, while the value quoted by MGH was 201.8 rad. This led to a value of 1.011 for the quotient of the dose assigned by MGH and the NBS dose interpretation in terms of NBS cobalt-60 gamma rays. The corresponding quotient in the MGH - IAEA comparison was quoted to us by the IAEA and the Harvard Medical School as having been 1.014. This difference is well within the uncertainty limits of the IAEA and the NBS pilot studies.

Another result concerned the slope of the dosimeter response-versus-depth curve obtained with the 10-MV Clinac-18 at MGH, which was about 1 percent smaller than the slope we obtained at 10 MV both with the Mevatron XII at NCI and the Clinac-18 at GWU Hospital. Considering that the geometries were not quite comparable (10 cm x 10 cm field size at a 10-cm depth at NCI and at GWU Hospital, at a 5-cm depth at MGH), this agreement is also satisfactory.

6. ANALYSIS OF THE MAGNITUDE OF THE UNCERTAINTY EXPECTED FOR THE PLANNED SURVEY FOR INDIVIDUALLY AND BATCH-CALIBRATED DOSIMETERS

The objective of the study reported here was to determine the number of TL dosimeters necessary per survey point to achieve a given limit of random uncertainty associated with the dosimeter handling, preparation and readout procedures agreed upon by BRH and NBS. The determination of the uncertainty was done by means of a statistical analysis based on the experimentally determined reproducibility of the TLD readings and was checked in part by means of the simulated survey discussed in Section 6.4 -- in both instances considering the case of individually calibrated and of batch-calibrated dosimeters. Considered were the uncertainties in the dose interpretation arising from each of the steps in the survey procedure, with the exception of the systematic uncertainties, common to surveyor and surveyed alike, which are inherent in the cobalt-60 gamma-ray calibration of the ion chamber and in the factor C_λ, both used in the determination of absorbed dose to water in the high-energy bremsstrahlung beam.

6.1 Procedure

It is envisioned that the survey protocol will require that the participants be furnished a Lucite phantom loaded with LiF TLD-100 dosimeters from a batch in which TLD sensitivity had been characterized either for each individual dosimeter or for the batch as a whole. The participants will be asked to deliver a prescribed absorbed dose to water (say, 100 rad) to a point at a 10-cm depth in the phantom, computing the dose as if the phantom material had been water. At the same time, TL dosimeters from the same batch will be irradiated by BRH with cobalt-60 gamma radiation from one of the standardized NBS sources at suitable calibration levels, in a similar phantom. BRH then will compute the high-energy bremsstrahlung absorbed dose to water delivered by the participant ($D_{partic.}$) at a 10-cm depth in the water phantom from the average dosimeter response of the dosimeters irradiated by the participant ($r_{partic.}$) at a 10-cm depth in the Lucite phantom as

$$D_{partic.} = r_{partic.} \, (D/r)_{BRH} \, Q^E_{Co}, \tag{3}$$

where $(D/r)_{BRH}$ is the quotient of absorbed dose over TLD response at a 10-cm depth in the Lucite phantom, as obtained from the current BRH cobalt-60 gamma-ray calibration curve, and Q^E_{Co} is defined in section 4.5.2. Even though we found Q_{Co}^{E} to be unity within the total uncertainty of our experiment (see sec. 4.5.2), the uncertainty inherent in the survey procedure has to contain the uncertainty associated with Q_{Co}^{E}. Also, in practice it may become necessary to add a fading-correction factor to eq (3) if the BRH calibration irradiations with the NBS cobalt-60 gamma-ray source are not going to be administered at approximately the same time as the high-energy bremsstrahlung irradiations are administered at the participating laboratories.

6.2 Reproducibility of Dosimeter Response

6.2.1 Procedure for characterizing reproducibility by batch (dosimeter identity not maintained). All available dosimeters were annealed and then irradiated identically and read out. A sub-group ("batch") was chosen such that the TL response of the included dosimeters could be characterized by a preselected standard deviation (S_B) about the mean. This batch then was used in the survey procedure, without regard to dosimeter identity. Work at BRH has shown that batch characterization in terms of S_B, once established, is maintained well through many experiment cycles at diagnostic irradiation levels. This was confirmed by our studies. However, we also demonstrated a temporary increase in sensitivity spread after a portion of the batch was used at therapy levels. (See the spread in the response to the sequence of test irradiations in figure 10, after the experiment involving a 400-rad irradiation.)

6.2.2 NBS experience with batch characterization of reproducibility of dosimeter response. Starting with a group of 200 dosimeters with a spread of about 12 percent between the responses of individual dosimeters to a constant exposure, it was possible to select a group of about 100 for which the value of S_B was about 2 percent. Obviously the value of S_B not only depends on the variability of the response among the dosimeters* but also on the rigor of

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*Strictly, the standard deviation from the average of the responses in the batch, S_B, is given by

$$S_B \doteq (S_D^2 + S_I^2/n)^{1/2},$$

where S_D is the standard deviation due to the variability among the dosimeters, S_I the standard deviation reflecting the reproducibility of individual dosimeter readings (see sec. 6.2.3) and n the number of dosimeters from which S_I and S_B were determined.(16) For the dosimeters used here, the second term proved negligible for values of n of the order of 10 or more.

the selection procedure. In practice, there is some lower bound on S_B. With the initial group of dosimeters used at NBS, 2 percent was relatively easy to obtain while 1.5 percent probably represented the practical limit for batch selection on the basis of a single set of readings. More rigorous procedures are possible, but the reproducibility of a smaller value for S_B from cycle to cycle would be questionable. For a 100-dosimeter batch selected by NBS from the initially normal population of 200, the value of S_B = 2 percent reproduced well over twelve test cycles. The selected population was again essentially normal.

6.2.3 Procedure for characterizing the reproducibility of individual dosimeters (identity maintained). All available dosimeters were annealed and then irradiated identically and read out. This procedure was repeated several times, in order to obtain a statistically valid average TL response for a given irradiation level. Since dosimeter response for a given irradiation level decreased from one to the next cycle (see fig. 10) and reader characteristics may not be identical from day to day, successive readings on a single chip cannot be used to directly determine a value for S_I, the uncertainty associated with an individual chip reading. Instead, S_I was determined indirectly from an examination of quotients of two successive readings on the same chip. An average of such quotients is then characterized by $S_I^{rel} = \sqrt{2}\, S_I$.

6.2.4 NBS experience with characteristics of the reproducibility of individual dosimeter response. In order to arrive at a value for S_I for 200 dosimeters, NBS irradiated and read them out in nine consecutive cycles. A value for S_I^{rel} of somewhat less than 1 percent was obtained, leading to a value of about 0.7 percent for S_I, or about one-half of the best feasible values for S_B. Thus, the increase in time and effort involved in maintaining dosimeter identity pays off in a considerable decrease in the uncertainty in the characterization of dosimeter response. There is evidence that, with the newer heater model in the hot-nitrogen reader, it is possible to achieve even further improvement.

6.3 Estimate of the Uncertainty in the Interpretation of Survey Doses, Based on a Statistical Analysis

The analysis involves assigning uncertainty limits to the individual steps in the computation of absorbed dose from the average of identically irradiated survey dosimeters (see eq [3]). Tables 5 and 6 give a review of

Table 5. Estimate of Random and Systematic Uncertainties in Dose Interpretation from LiF (TLD-100) Dosimeter Response (see section 6.1)

Quantity	Random Uncertainty[a]					Systematic Uncertainty[b]	
	Formulae for computation dosimeter-response characterized		Computed value, %			due to	value, %
			number of dosimeters	dosimeter response characterized			
	by batch	individually		by batch	individually		
$(D/r)_{BRH}$	$3\, S_B/\sqrt{n}$ for $S_B \doteq 2.0$	$3\, S_I^{rel}/\sqrt{n}$ for $S_I^{rel} \doteq 1.0$	n = 25[c] 50 100[d]	1.2[c] 0.9 0.6[d]	0.6 0.4 0.3	positioning of phantom timing of exposure	0.2
$r_{partic.}$	$3\, S_B/\sqrt{n}$ for $S_B \doteq 2.0$	$3\, S_I^{rel}/\sqrt{n}$ for $S_I^{rel} \doteq 1.0$	n = 9[c] 16 25	2.0[c] 1.5 1.2	1.0 0.8 0.6		
Q_{Co}^{E}	$3\, S_B\left(\frac{1}{n_{Co}} + \frac{1}{n_E}\right)^{1/2}$ for $S_B \doteq 2.0$	$3\, S_I\left(\frac{1}{n_{Co}} + \frac{1}{n_E}\right)^{1/2}$ for $S_I^{rel} \doteq 1.0$	$n_{Co} = n_E =$ 25[c] 50 100	1.7 1.2 0.8	0.9[c] 0.6 0.4	positioning of phantoms (both sources), timing of exposure (cobalt source) timing of exposure (high-energy bremsstr. source) uncertainty in ionization measurement (high-energy bremsstr. source)[e]	0.4 0.5 0.5

(a) n stands for the number of dosimeters, with a subscript where necessary.

(b) Upper bound to systematic error.

(c) Chosen for this estimate.

(d) Chosen for determination of reproducibility of dosimeter response.

(e) Included are uncertainties due to monitor drift, timing errors and variability in ion-chamber readings.

Table 6. Computation of Total Uncertainties[a]

quantity	uncertainty, %		row sum, %	
	random	systematic[b]	algebraic sum	summed in quadrature
$D_{BRH} \cdot r$	$[0.6^2 + 2.0^2]^{1/2}$ $= 2.1$	0.2	2.3	2.1
Q^E_{Co}	0.9	1.4	2.1	1.7
		grand totals:	4.4%	2.7%

(a) The values indicated are for the chosen or recommended numbers of dosimeters for the determination of each quantity, as indicated by the footnotes in Table 3.1.

(b) The individual parts of each systematic uncertainty were summed algebraically.

the results, computed on the basis of the values for S_B and S_I^{rel} discussed in Section 6.2. Random uncertainties were computed as three times the standard deviations from the average of the dosimeter readings, on the basis of several choices for the number of dosimeters employed in each phase. Where required, the total standard deviations corresponding to multi-component expressions were obtained by compounding in quadrature the standard deviations of each part of these expressions. The uncertainty in the quotient, Q_{Co}^E, was considered to enter into eq (3) as a systematic uncertainty. Numbers of dosimeters and mode of dosimeter-response characterization are shown in the footnotes of table 5 and the final results for the chosen numbers of dosimeters and modes of response characterization are given in table 6.

6.4 Check on Uncertainty Estimates by an In-House Simulation of One Survey Cycle

This study was undertaken in order to check the validity of the statistical model used for the assignment of uncertainties in the previous section. For this purpose, a typical survey cycle was mimicked almost in its entirety by an in-house experiment. Since suitable high-energy bremsstrahlung is not available at NBS, cobalt-60 gamma radiation was used for the dosimeter irradiations simulating the "unknown" irradiations of the survey. Since the "unknown" irradiations actually were administered simultaneously with the known cobalt-60 calibration irradiations, the systematic uncertainties due to phantom positioning and timing were eliminated from the estimate of the uncertainty in the dose interpretation. Also, the uncertainty in Q_{Co}^E was excluded.

Eighty-one dosimeters that had been prepared in the usual way were irradiated in a Lucite phantom to known absorbed-dose levels of cobalt-60 gamma radiation. Some of these dosimeters then were assigned the role of calibration dosimeters, while the remaining dosimeters were considered to have received "unknown" doses. Nine irradiation levels were used, with absorbed doses to water ranging from 100 to 300 rad, distributed symmetrically about 200 rad, which was supposed to correspond to the requested irradiation level. Nine dosimeters were used per irradiation level.

All dosimeters were read out in close succession and calibration curves were prepared, both on the basis of individual response characterization and of response characterization by batch. Table 7 shows the results for two

Table 7. Comparison, Uncertainty of Results of Simulated Survey and Computed Uncertainty Estimates

Number of "unknown" points[a]	Number of points[a] for fit	Standard deviation percent[b]	Spread, difference between dose interpretation on "unknowns" and "true" dose, percent[b]
Batch Characterization of Reproducibility (Simulated Survey):			
4	5	2.1	- 1.8% to + 1.1%
5	4	1.7	- 2.3% to + 1.5%
Computed Uncertainty Estimates:			2.9% (algebr. sum) 2.3% (summed in quadrature)
Individual Characterization of Reproducibility (Simulated Survey):			
4	5	0.8	- 0.45% to + 0.16%
5	4	1.5	- 0.99% to + 0.92%
Computed Uncertainty Estimates:			1.8% (algebr. sum) 1.3% (summed in quadrature)

(a) 9 dosimeters per point

(b) From regression line

different assignments of the irradiated dosimeters to the "calibration" and "unknown-dose" groups. Also shown are corresponding results of the uncertainty estimates based on the simplified statistical model. In all cases, the actual deviations between reported and assigned ("true") doses are seen to have been well within the uncertainty estimates. It is to be expected that, for a larger sample of "unknowns", the difference between actual deviations and computed estimates would have been smaller and that some of the deviations in fact would have been larger than the estimated uncertainties.

7. RECOMMENDATIONS

It is recommended that BRH proceed during the survey much as NBS proceeded during the various calibration and test phases, eliminating as much as possible intermediate steps that could increase the already relatively high estimated overall uncertainty for the dose interpretation. Specifically, we have the following recommendations:

(a) Prior to the start of the survey, serious consideration should be given to replacing batch characterization of dosimeter response by individual dosimeter-response characterization in all phases of the survey, and to replacing the original heater in the hot-nitrogen TLD reader by the improved heater now sold by the Harshaw Chemical Company, if this has not been done already.

(b) A Lucite cube with a 20-cm side length should be used as a phantom.

(c) Nine dosimeters should be positioned next to each other near the phantom mid line, at a 10-cm depth in the phantom and, if desired, also at several other depths $\geq$ 5 cm.

(d) The participants should be asked to administer 100 rad to water at a 10-cm depth in the phantom, using a 10-cm x 10-cm field at this depth.

(e) At least one test cycle consisting of irradiation of all dosimeters in the batch at a constant level below 10 R followed by readout about one day after irradiation should be inserted between any two survey cycles.

(f) For each survey cycle, the relationship between dosimeter response and absorbed dose to water should be obtained with cobalt-60 gamma radiation from a standardized NBS source, covering absorbed doses to water at least over the range from 50 to 300 rad. This relationship should be determined from the response of sets of dosimeters irradiated at approximately the same time as the participants administer their survey irradiations, and read out along with the dosimeters irradiated by the participants.

(g) Regardless of whether batch or individual calibration is used, the survey-dosimeter response should be adjusted to the average of the dosimeter response during the test cycles immediately preceding and following the survey cycle.

(h) The average adjusted response of the dosimeters irradiated at any one depth in the phantom should be evaluated in terms of absorbed dose to water, utilizing the current cobalt-60 gamma-ray calibration data discussed in (f).

(i) The relationship between absorbed dose to water and depth in Lucite, normalized to a depth of 10 cm, should be obtained from the data computed in (h), for a later study of slope as a function of nominal peak bremsstrahlung energy.

(j) At least twice during the survey BRH should provide NBS with a phantom loaded with dosimeters for irradiation with cobalt-60 gamma radiation at a level unknown to BRH at roughly the same time as the irradiations are administered by the current set of participants, for evaluation along with the participants' dosimeters, for the purpose of measurement assurance.

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9. REFERENCES

1. Soares, C.G. and Ehrlich, M., Concerning $Li_2B_4O_7$ Thermoluminescence Dosimeters, Med. Phys. 6, 312 (1979).
2. See, e.g., Bjärngard, B.E., Rudén, R.-I. et al, Evaluation of the 1977 IAEA Pilot Study of Postal Dose Intercomparison (TLD) for Orthovoltage X-Ray Therapy, Proceedings of a Symposium on National and International Standardization of Radiation Dosimetry, Atlanta, December 1977, Vol. I, 319, International Atomic Energy Agency, Vienna (1978).
3. Ohlhaber, T.R., Design of the BENT Dosimetry System and its Application to a Nationwide Mammography Quality Assurance Program, Symposium on Biological Effects, Imaging Techniques, and Dosimetry of Ionizing Radiation, Bureau of Radiological Health, 1979 (to be published).
4. LaRiviere, P., Varian Associates, private communication.
5. Levy, L.B., Waggener, R.G., Wright, A.E., Measurement of Primary Bremsstrahlung Spectrum from an 8-MeV Linear Accelerator, Med. Phys. 3, 173 (1976).
6. Spencer, L.V. and Fano, U., Penetration and Diffusion of X-Rays. Calculation of Spacial Distributions by Polynomial Expansion, J. Research, NBS, 46, 446 (1951); for the results referring to a plane-parallel source, see e.g., Goldstein, H., The Attenuation of Gamma Rays and Neutrons in Reactor Shields, prepared for the Division of Reactor Development, U.S. Atomic Energy Commission (1957).
7. Calibration and Related Measurement Services of the National Bureau of Standards, NBS Special Publication 250 and associated Appendix, U.S. Government Printing Office (1978-1979).
8. Pendurkar, H.K., Boulanger, R., Ghoos, L., et al, Energy Response of Certain Thermoluminescent Dosimeters and their Application to the Dose Measurement, Proceedings, Third International Conference on Luminescence Dosimetry, Risø Report No. 249, Part III, p. 1089, Danish Atomic Energy Commission, Research Establishment Risø (1971).
9. Spencer, L.V., and Lamkin, J., Slant Penetration of γ-Rays in H_2O, National Bureau of Standards Report 5944 (1958).
10. Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures, ICRU Report 24, International Commission on Radiation Units and Measurements (1976).

11. Naylor, G.P., Thermoluminescent Phosphors: Variation of Quality Response with Dose, Phys. in Med. and Biol. 10, 564 (1965).
12. Ehrlich, M., Thermoluminescence Response of LiF to X- and Gamma Rays; a Study of Rate and Energy Dependence over a Wide Range of Exposures, Proceedings, First International Congress of Radiation Protection, Rome, 1966; Pergamon Press, NY (1968).
13. Bagne, F., A Comprehensive Study of LiF TL Response to High Energy Photons and Electrons, Radiology 123, 753 (1977).
14. Ehrlich, M., Seltzer, S.M., Bielefeld, M.J., Trombka, J.I., Spectrometry of a ^{60}Co Gamma-Ray Beam Used for Instrument Calibration, Metrologia 12, 169 (1976).
15. For the cobalt-60 data (100 cm SSD) see, e.g., Central Axis Depth Dose Data for Use in Radiotherapy, Cohen, M., Jones, D.E.A., and Greene, D., editors, Supplement Number 11, British Journal of Radiology, British Institute of Radiology, London (1978); and for the 4-MV data (80 cm SSD) see, e.g., Peterson, M. and Golden, R., Dosimetry of the Varian Clinac-4 Linear Accelerator, Radiology 103, 675 (1972).
16. Snedecor, G.W. and Cocheran, W.G., in Statistical Methods, Chapter 10, 6th Ed., Iowa State Univ. Press, Ames, IA (1967).

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This is the final report covering the work performed under an interagency agreement between the National Bureau of Standards and the Bureau of Radiological Health during the fiscal years 1978 and 1979. A thermoluminescence dosimetry system suited for a survey of high-energy bremsstrahlung in U. S. radiation-therapy departments was selected and calibrated. The experiments leading to the choice of the recommended operational characteristics, including dosimeter handling, annealing and readout, dosimeter stability in the contemplated mode of operation, dosimeter response over the photon-energy range to be covered, irradiation geometry and irradiation level are treated in detail. Results are reported of a pilot study involving the shipment of a typical survey assembly (a plastic phantom loaded with a set of dosimeters) for irradiation in one U. S. therapy department and the overall uncertainty of the proposed survey procedure is discussed.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)

Calibration; dosimetry; high-energy bremsstrahlung; operational characteristics; radiation therapy; recommendations; selection of thermoluminescence dosimetry system; survey; thermoluminescence; United States.

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