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Quality Assurance for Measurements of Ionizing Radiation

Edited by E. H. Eisenhower

National Bureau of Standards
U.S. Department of Commerce

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Commission

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ABSTRACT

This report describes results of a three-year program that will enable the Nuclear Regulatory Commission to improve, demonstrate, and document traceability of its measurements to the national physical measurement standards for ionizing radiation. The principal actions taken were: (a) characterization of the response of a thermoluminescence dosimetry system used for routine surveillance of nuclear facilities; (b) characterization of the response of six models of portable survey instruments; and (c) implementation of routine quality assurance services that will demonstrate that laboratories which calibrate survey instruments for the NRC are sufficiently consistent (in agreement) with national measurement standards. Tests of the TLD system were performed as specified in American National Standard N545-1975, plus several additional tests not contained in that document. Measurement assurance tests were conducted for the NRC Region-1 laboratory. The response of the survey instruments was determined for photon energies as high as 6.5 MeV, and for beta particles of various energies, including those emitted by ^{133}Xe gas. The basic principles under which the long-range interactive MQA program will operate were developed and documented, and the feasibility of the program was demonstrated.

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ACKNOWLEDGMENTS

This report describes the results of activities conducted by the Center for Radiation Research (CRR) of the National Bureau of Standards for the Nuclear Regulatory Commission. Because of the breadth of these activities, many members of the CRR staff were involved. Those who had significant involvement are identified at the beginning of each of the three major parts.

The guidance, cooperation, and assistance provided by NRC staff members is appreciated. These include Dr. Phillip Reed (Office of Nuclear Regulatory Research), Dr. Lawrence Cohen (Office of Inspection and Enforcement), Frank Costello (Region 1), and Michael Slobodien (formerly of Region 1).

QUALITY ASSURANCE FOR MEASUREMENTS OF IONIZING RADIATION

EXECUTIVE SUMMARY

The effectiveness of a regulatory program is directly proportional to the quality of the measurements made for the purpose of enforcing the program. Measurement quality is readily interpreted to mean the degree of agreement with the national physical measurement standards maintained by the National Bureau of Standards (NBS). A program of work was undertaken by NBS to improve the agreement with national standards for particular measurements made by the NRC for operation of its inspection and enforcement programs.

The three major elements of the work program were: (a) characterization of the response of a thermoluminescence dosimetry system used for routine surveillance of nuclear facilities; (b) characterization of the response of six models of portable survey instruments; and (c) implementation of routine quality assurance services that will demonstrate that laboratories which calibrate survey instruments for the NRC are sufficiently in agreement with the national measurement standards.

Characterization of the Thermoluminescence Dosimetry System

The system consists of the Panasonic thermoluminescence dosimeter (TLD) reader Model 702E and the associated Model UD-801 dosimeters. This particular dosimeter contains one lithium-borate element under plastic with a thickness of 14 mg/cm^2, a second lithium-borate element under plastic of 300 mg/cm^2 thickness, and two calcium-sulfate elements, both under 700 mg/cm^2 of lead. The tests that were conducted are those specified in American National Standard N545-1975, with some modification of the performance specifications to conform with NRC Regulatory Guide 4.13. Additional tests were conducted as required by the NRC for the envisaged dosimeter use. Performance of the system was determined and evaluated independently for the lithium-borate elements and the two calcium-sulfate elements.

Some general conclusions are:

- This particular TLD system is one of the systems suitable for routine surveillance of nuclear facilities.
- The system is suitable for both photon and beta-particle dosimetry.
- Failure to satisfy a specified performance requirement is caused by the dosimeter, rather than by the reader.

Those conclusions are based on these major findings:

- The dosimeter fails to meet performance specifications for only two characteristics -- energy dependence and directional dependence.
- Performance of the lithium-borate elements is inferior to that of the calcium-sulfate elements for a majority of the test characteristics. The obvious exception is response to beta particles.

- Liquefaction of the lithium-borate elements under conditions of high humidity and temperature may present deployment limitations.

- Dosimeter response may be drastically reduced if the dosimeters are shielded by a supporting pole.

- When immersed in a semi-infinite cloud of ^{133}Xe gas, only the lightly-filtered lithium-borate element responded significantly.

The findings and conclusions lead to several recommendations:

- Response of the lithium-borate elements should not be relied upon when good reproducibility is required for readings at levels close to natural background.

- The thickness of the lead filter over the calcium-sulfate elements should be reduced so as to provide less attenuation of the incident radiation.

- Response of the calcium-sulfate elements should be improved, in the form of reduced directional dependence, through judicious lateral shielding by a high-atomic number material incorporated into the dosimeter.

Characterization of Survey Instruments

Six models of commercial survey instruments used by NRC inspectors were studied, and the results are based on a study of only one instrument of each model. The particular models, and the type of detector employed in each, are:

- XETEX Model 305B Digital Exposure Rate Meter (GM)
- Ludlum Model 16 Analyzer (sodium iodide)
- Eberline Ion Chamber Survey Meter Model RO-2A (ionization chamber)
- Eberline Geiger Counter Model E-520 (GM)
- Eberline Micro-R/h Meter Model PRM-7 (sodium iodide)
- Teletector Model 6112B (GM).

The instruments were studied in photon beams over an energy range from 40 keV to 6.5 MeV; in beta-particle beams with maximum energies between 200 keV and 2 MeV; immersed in the gaseous ^{133}Xe beta-particle emitter; and, where appropriate, in close-to-monoenergetic electron beams with energies between 100 and 400 keV.

In general, instrument response to photon beams with energies up to 1250 keV was as expected, with the GM and sodium-iodide instruments showing their typical large energy dependence. The ion-chamber instrument, on the other hand, showed the typical lack of energy dependence for detectors of this type. A discrepancy between NBS study of the PRM-7 instrument and the calibration provided by the manufacturer illustrated the importance of calibration with a radiation source that has an energy spectrum similar to the radiation to be measured in a field situation.

Studies of the Teletector instrument showed an appreciable effect of battery condition on the response, even when the battery voltage is above the minimum indicated as acceptable by the black line.

When exposed to 6.5-MeV photons, behind 2.5 cm of Lucite to establish electron equilibrium, both the Teletector and the RO-2A instrument responded 20 percent higher than for gamma radiation from ^{137}Cs. The other instruments showed greater departure from their response to this reference radiation, although all except the two sodium-iodide instruments erred in the "safe" direction, i.e., their readings were higher in the 6.5-MeV field.

Only the RO-2A instrument responded to beta particles over the entire energy range studied, showing a sensitivity to 2-MeV beta particles that is within 20 percent of its sensitivity to ^{137}Cs gamma-ray photons. As expected, its sensitivity decreases considerably for lower-energy beta particles. Compatible results were obtained from studies of this instrument's response to monoenergetic electron beams.

When immersed in a ^{133}Xe gaseous atmosphere, five of the six instruments appeared to respond only to the gamma radiation. The RO-2A instrument responded also to the beta radiation, but with very low sensitivity.

Based on these results, the recommendations are:

- Within its range of exposure rates, the ionization-chamber instrument should be used for quantitative measurements.
- Instruments that use GM or sodium-iodide detectors should be used for detection of radiation because of their high sensitivity, but should not be used for measurements.
- Special efforts should be made to replace batteries in the Teletector instrument well before the voltage falls to the minimum acceptable (blackline) level.
- When an instrument is used to survey radiation with energies in the vicinity of 6 MeV, readings should be taken behind increasing thicknesses of plastic in order to establish an attenuation curve in plastic for the radiation being surveyed. This curve may then be used for estimating dose equivalents at depths of interest.
- Of the instruments studied, the RO-2A should be used for measurements of beta-particle fields. Such measurements should, however, be regarded as approximations because of the strong dependence of instrument sensitivity on beta-particle energy.

Implementation of Quality Assurance Service

At the request of the NRC, a program was developed to provide increased assurance that survey measurements made routinely by inspectors are sufficiently accurate. The program is based on a new kind of interaction between NBS and those laboratories that calibrate radiation survey instruments used by NRC inspectors. Another aspect of the program is the quality control that should be practiced by such laboratories.

In the past, the principal method used in attempts to achieve measurements at the field level that were consistent with (i.e., in agreement with) the national physical measurement standards maintained by NBS was calibration of radiation instruments or sources by NBS. These calibrated items have then

been used as transfer standards at an intermediate level to, in turn, calibrate instruments used at the field level. The basic difficulty with this method is that the quality of the field-level measurements is unknown, partly because the quality of the instrument calibration is unknown.

The degree of quality assurance could be improved if the performance of the calibration laboratory were evaluated periodically by NBS, in a manner that demonstrates consistency with the national standards. The documentation of this evaluation would result in what might be called "measurement traceability," in contrast to the "instrument traceability" resulting from instrument calibration without performance evaluation.

At the beginning of this project, NBS was asked to establish improved interactions, including periodic performance evaluation, with four laboratories: Argonne National Laboratory, Brookhaven National Laboratory, Eberline Instrument Corporation, and Lawrence Livermore National Laboratory. Each was contacted to determine its interest in participating in NBS services that would result in demonstrated consistency with NBS, and all responded favorably. Subsequently, it was requested by NRC that Lawrence Berkeley Laboratory and the DOE Radiological and Environmental Sciences Laboratory also be contacted.

To obtain the information required for the planning and conduct of future consistency demonstration services, a questionnaire was distributed. It requested a description of the characteristics of the photon beam(s) to be used for calibration of instruments circulated by NBS for performance evaluation. It also requested information on the in-house standards used by the participating laboratory, the maximum acceptable difference between the calibration factors determined by NBS and by the participant, the desired frequency of consistency demonstation services, and the status or intentions regarding in-house constancy checks.

Based on responses to the questionnaire, procedures were developed for conduct of periodic consistency demonstration services. In accordance with these procedures, the instruments were shipped to the first participant, Argonne National Laboratory, in January 1984. The agreement between NBS and this laboratory was well within the limits previously agreed upon.

It is recommended that the laboratories that calibrate survey instruments for NRC inspectors adopt an interactive quality assurance program with NBS. It would include:

- Initial calibration by NBS of the laboratory's in-house standard.
- Demonstration of consistency with NBS through periodic consistency demonstration services.
- Constancy checks on the in-house standard and calibration procedures by the participating laboratory.
- Recalibration of the in-house standard only if the need is determined by constancy checks or consistency demonstration results.

The program should first be adopted for photon radiations, after which it should be extended to other types of radiation, such as beta particles and neutrons.

INTRODUCTION

Measurements of ionizing radiation for the purpose of enforcing regulations that protect the public from radiation hazards must be sufficiently accurate for effective enforcement. Such measurements also should be made on a common basis by the regulator and regulatee, to avoid potential conflicts and disagreements that may reach culmination in a court of law. Therefore the effectiveness of a regulatory program is dependent upon ability of the regulator to demonstrate convincingly that the quality of the measurements can be defended. A common interpretation of measurement quality is consistency with the national physical measurement standards maintained by the National Bureau of Standards. If the degree of consistency is high, the quality of the measurement is defensible.

Public concern about radiation hazards, coupled with an increasing tendency to question the adequacy of radiation measurements, has resulted in the need to improve the degree of consistency of regulatory measurements with the national measurement standards. In addition, there is increasing need to demonstrate and document improved consistency so that questions and expressed concerns about measurement adequacy can be resolved promptly and favorably. These needs must be satisfied for routine enforcement of regulations, and for response to emergencies, when crucial decisions must be made promptly. Measurements that support such decisions must be made with instruments whose reliability has been demonstrated, whose accuracy has been established in terms of the national standards, and whose response has been characterized for the particular types, energies, and intensities of radiation being encountered. In many instances, the adequacy of radiation measurements being made for regulatory purposes is unknown, in the sense that the degree of consistency with the national measurement standards has not been demonstrated or documented.

The purpose of this three-year program was to: (a) characterize the response of a thermoluminescence dosimetry system used for routine measurements carried out for enforcement of regulations; (b) characterize the response of specific types of survey instruments over a range of radiation properties of interest for radiation protection measurements; and (c) implement quality assurance services to demonstrate periodically that regulatory measurements are in adequate agreement with the national physical measurement standards maintained by the National Bureau of Standards. The work emphasized measurements of interest to the Nuclear Regulatory Commission for operation of its Inspection and Enforcement (I&E) programs.

Standardized radiation fields were used to characterize the response of instruments and dosimetry systems utilized by NRC enforcement officials and by NRC licensees, including portable survey instruments, personnel dosimeters, and environmental monitoring systems. Special emphasis was given to work on the thermoluminescence dosimetry (TLD) system that I&E uses for routine environmental and personnel monitoring in the vicinity of operating nuclear facilities.

The mechanisms necessary for demonstrating that regulatory I&E measurements are traceable to the national standards were developed and implemented on a routine basis between NBS and the laboratories that calibrate instruments used in I&E programs. Included are periodic evaluations of the calibration services provided to the NRC, which were identified and documented. This represents a major step forward in assuring the quality of measurements made by I&E personnel. Since the same quality assurance services will be made available to laboratories that calibrate instruments for licensees and agreement states, uniformity of measurements also is expected to improve substantially on a national basis.

This final report describes the activities and accomplishments during the entire three-year program.

PART A

CHARACTERIZATION OF THE THERMOLUMINESCENCE DOSIMETRY SYSTEM

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PART A

CHARACTERIZATION OF THE THERMOLUMINESCENCE DOSIMETRY SYSTEM

1. The Thermoluminescence Dosimetry System

The system consists of the manual Panasonic thermoluminescence dosimeter (TLD) reader, Model 702E and the associated Model UD-801 AQ dosimeters. The reader is interfaced with a microcomputer for data retrieval and processing.

Table A-1 shows the composition and dimensions of the dosimeters' radiation-sensitive TL elements and the composition and thickness of the filters built into the holders. The relationship between the four elements, held in a plate that slides into a holder carrying the filters and the dosimeter identification code, is shown in Figure A-1. Readout and annealing are accomplished by (a) optical heating of the backing of the TL elements, (b) TL signal conversion by a photomultiplier (PMT) to voltage pulses, and (c) integration of the PMT pulses over a suitable time interval. Figure A-2 shows a schematic of the reader assembly and of the readout and annealing sequence. The power of the heating lamp and the resulting timing of the readout and annealing sequences differ for the manual and automatic reader models. In the manual reader, employing a low-power halogen heating lamp (15V, 20A, maximum), the entire sequence takes about five seconds, with the readout gate open for less than one-half second. In the automatic reader, the sequence takes about one second.

Table A-1. Description of the UD-801 AQ Dosimeters

TL Element			Filters Built into Holder
Designation	Dimensions	Chemical (granular)	
# 1	3 mm in diameter, ~0.1 mm thick (monograin layer), bonded to plastic-film substrate backed by a carbon film, and covered with 10 mg/cm^2 of Teflon	$Li_2B_4O_7$:Cu	14 mg/cm^2 of plastic
# 2		$Li_2B_4O_7$:Cu	300 mg/cm^2 of plastic
# 3		$CaSO_4$:Tm	700 mg/cm^2, plastic plus lead
# 4		$CaSO_4$:Tm	700 mg/cm^2, plastic plus lead

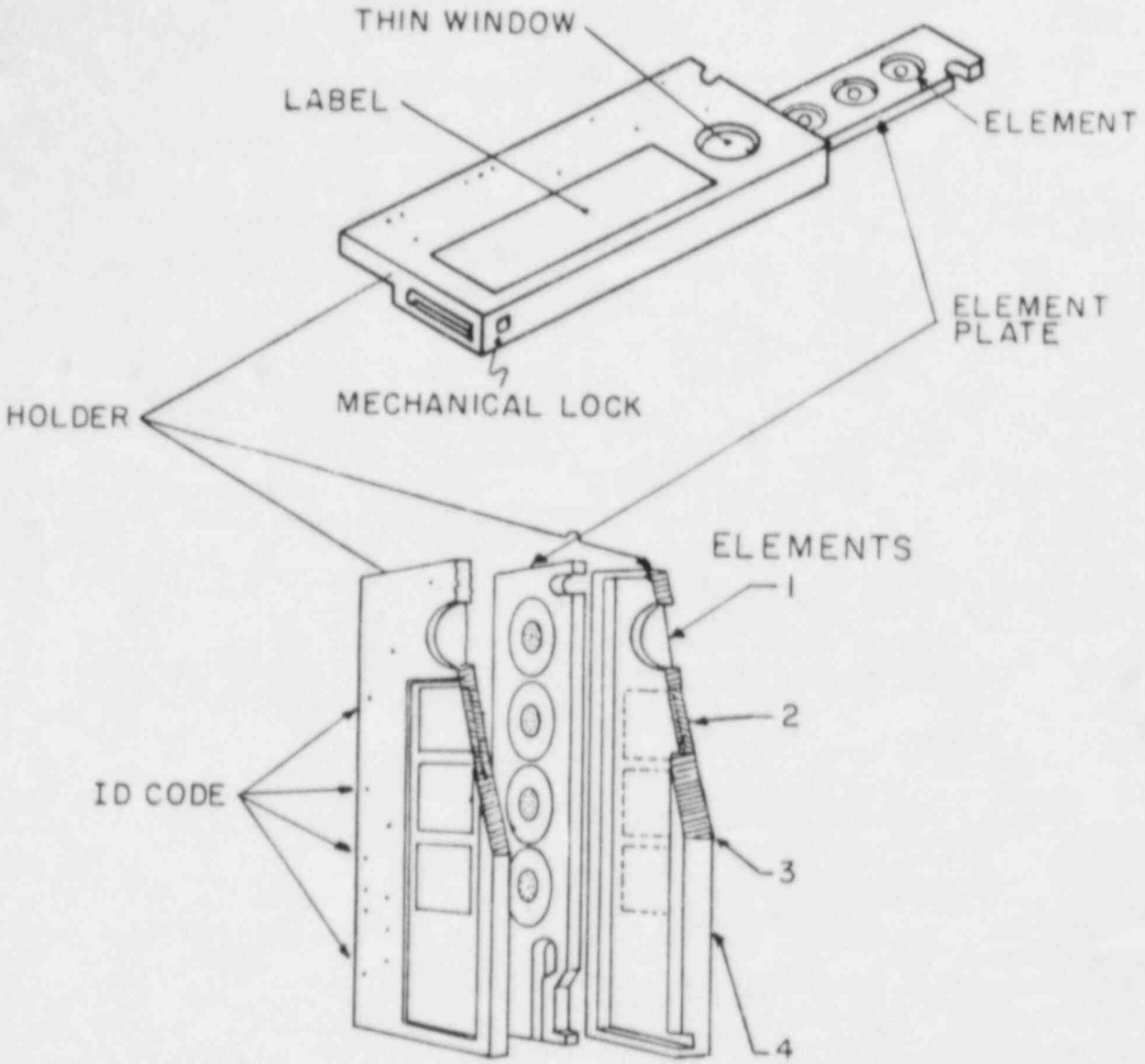
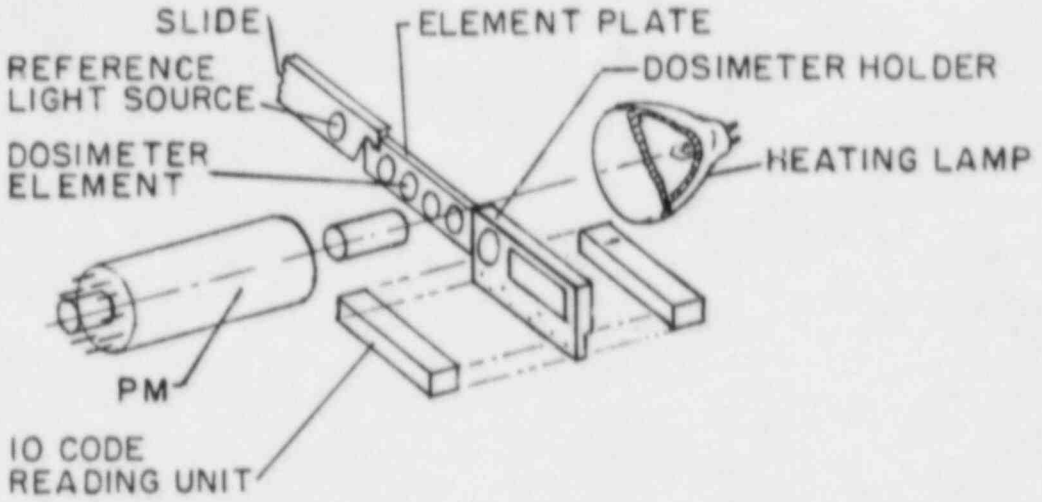


Figure A-1 Relationship Between the TLD Elements in their Holder



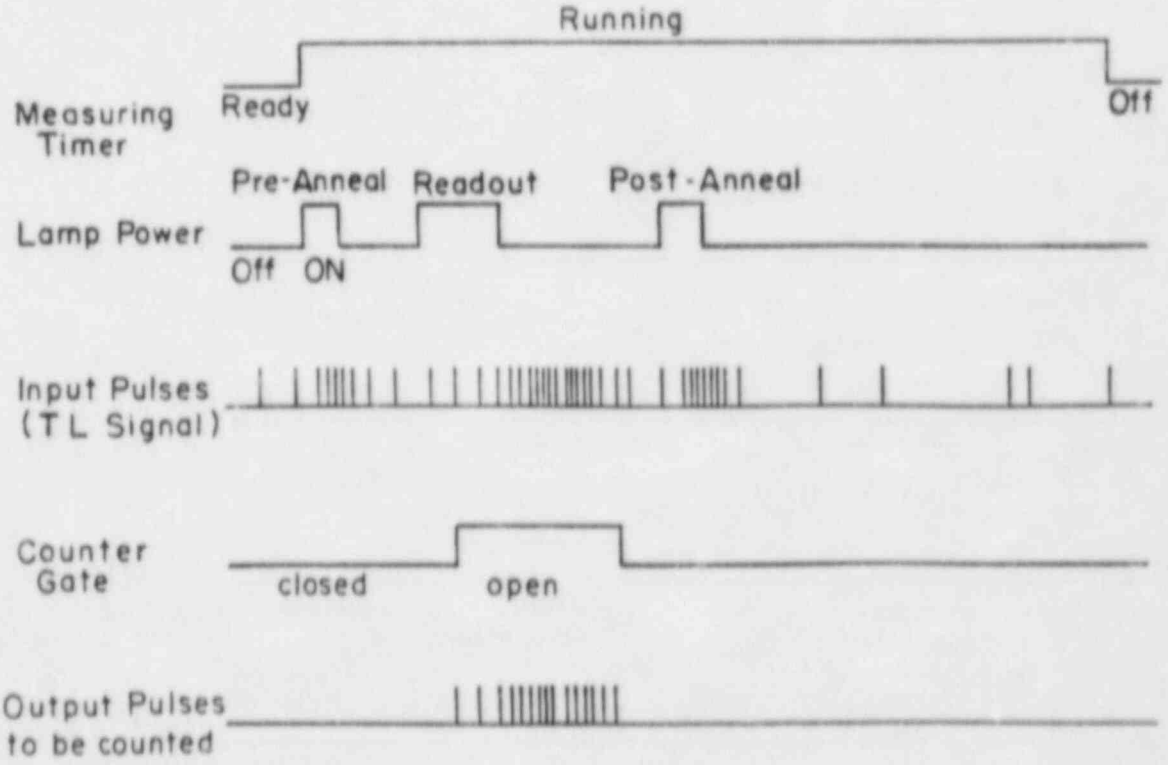


Figure A-2 Schematic of Reader Assembly and of Readout and Annealing Sequence

2. Test Methods

The tests carried out covered mainly those in American National Standard N545-1975 [1], with the methods for test evaluation modified to conform with Nuclear Regulatory Commission (NRC) Regulatory Guide 4.13 [2]. Additional tests were performed as required by the NRC for the envisaged TLD application.

For the Panasonic Model UD-801 AQ dosimeters used, the only averaging process carried out was that applying to the responses (or exposure interpretations from these responses) of the $CaSO_4$:Tm elements 3 and 4, which have identical filtration. Averaging the responses of different types of phosphors would be meaningless. Averaging the dose interpretations obtained from the responses of different types of phosphors, either with identical or different filtration or obtained from the responses of the same type of phosphor with different filtration, may lead to meaningful results for some of the tests, but would cause a considerable loss of information regarding the performance of the individual dosimeter elements. Therefore, this procedure would reduce the possibility of arriving at useful recommendations regarding dosimeter design and applicability.

Also in the rest of the performance specifications given in the standard, whenever the criterion was worded in terms of percent difference between the measured and the reference response, it was modified to specify instead the range of acceptable measured responses.

3. General Test Protocol

At the start of the program, a sequence was evolved for individual dosimeter characterizations, test irradiations and readouts, which, with the variations necessitated by the particular compliance tests, was followed throughout the program:

3.1 Characterization of the Response of Individual Dosimeter Elements

The dosimeters were given ^{60}Co gamma-ray exposures each corresponding to 10 μR/h for 90 days (i.e., exposures of 21.6 mR) requiring irradiation times of about 2 minutes. Fifteen dosimeters were irradiated simultaneously in an array ensuring uniformity of the radiation-beam cross section over the dosimeter areas and absence of a significant amount of scatter from dosimeter to dosimeter. For tests requiring more than 15 dosimeters, sets of 15 dosimeters each were irradiated 15 minutes apart to account for the manual readout rate of one dosimeter per minute. This ensured that fading times for all dosimeters varied by not more than 15 minutes. The dosimeters were read out approximately 18 hours after irradiation. Dosimeter characterizations were performed between any two test cycles and the individual test readings were divided by the average of the particular dosimeter-response characterization before and after the test. (As a rule, the characterization readings before and after the tests were equal to within one standard deviation; no trends were observed with dosimeter use.)

3.2 Test Irradiations

While specific irradiation conditions depended on the type of test, the general precautions regarding dosimeter positioning in the radiation fields and timing of laboratory irradiations relative to readout were similar to those discussed in 3.1. The irradiations for most tests were performed in the same geometry as the irradiations for characterizing the response of the dosimeter elements (see 3.1). For the studies of the dependence of response on energy and direction of the radiation, the dosimeters were irradiated singly. During laboratory background irradiations at ambient temperatures, the dosimeters were stored in their trays. All tests were performed with a number of replicates sufficient to ensure compliance with the requirements of the standard at the 95-percent confidence level.

3.3 Readout of Dosimeter Elements and Preparation for Subsequent Use

Readouts were performed manually at an average rate of one dosimeter per minute, with reader checks after every fifth dosimeter. All dosimeter readings, reference-element readings, dosimeter identification numbers, and information on element type and dark-current levels were stored automatically in the on-line computer. In the initial stages of the work, dosimeters were reread one hour after the first reading to study the level and reproducibility of residuals. This procedure was discontinued after it had been established that, for the irradiation levels used for the tests, residuals were negligibly small. Preparation for the next round of dosimeter use consisted in one characterization run immediately before re-use. Also, when the dosimeters had been stored for more than two days since the last readout, they were subjected to an additional readout immediately preceding the characterization irradiation, in order to eliminate the effect of the natural background.

4. Reader Studies

4.1 Comparison of Performance of the Manual and Automatic Readers

Figures A-3 and A-4 show the results of experiments done at NBS and at the NRC Region 1 (King of Prussia) laboratory to compare performance of the manual and automatic reader, respectively. The purpose of the experiments was (1) comparing the glow curves obtained with the lithium borate and the calcium sulfate elements of the Panasonic UD-801 dosimeters read in both the manual and the automatic reader, and (2) establishing whether the gating circuits in the two readers are adjusted for integration over comparable (and adequate) portions of the respective glow curves.

To obtain the glow curves generated by the two readers, PMT voltage pulses due to the TL signal were counted with multi-channel analyzers in the scaling mode over a period of approximately five seconds with the slower manual reader and of approximately one second with the automatic reader. The gating-pulse trains that start and stop the PMT pulse integration were recorded with the same analyzers and matched to the glow curves. (See the entries "READ GATE" on the graphs.)

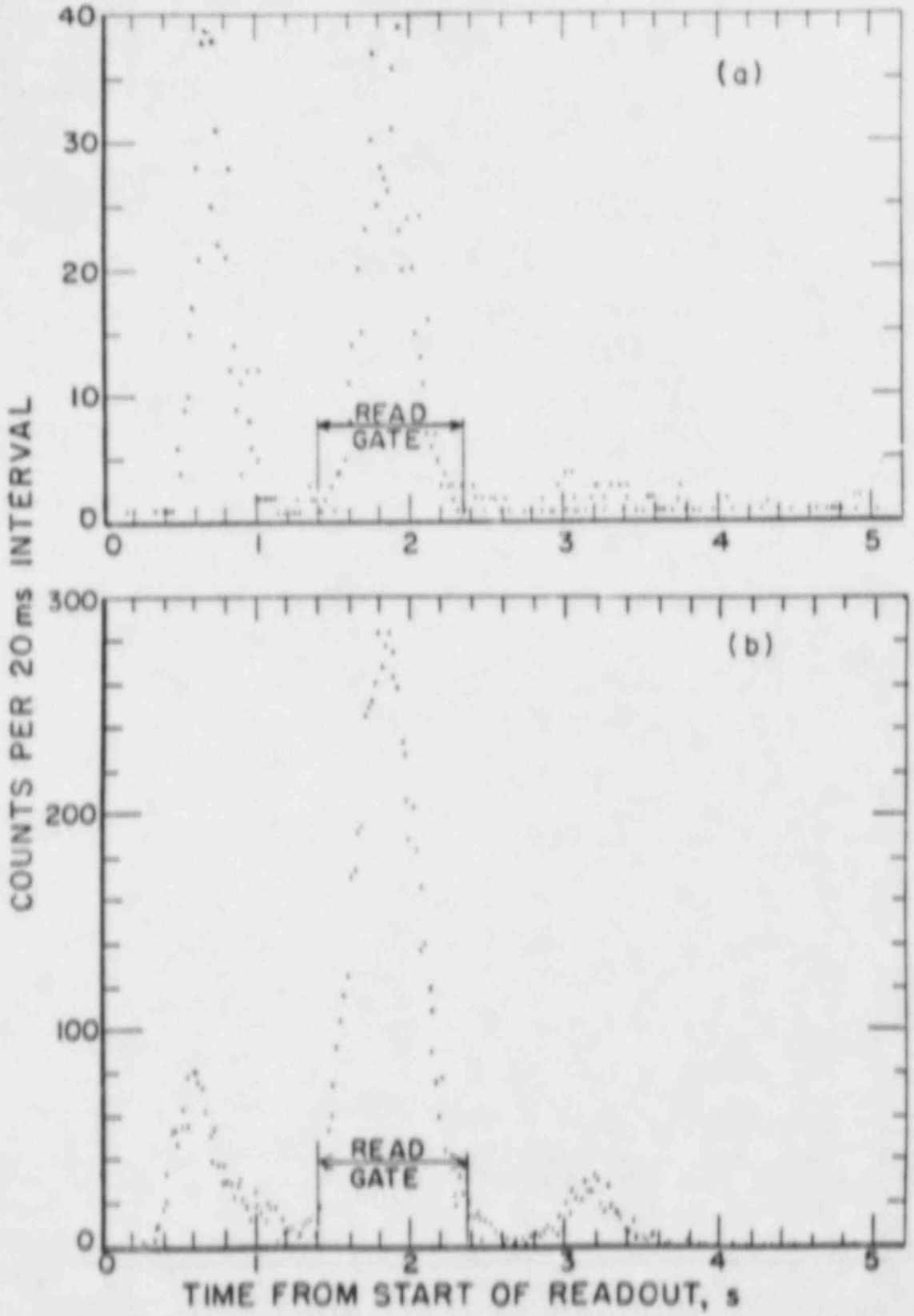


Figure A-3 Glow Curves of UD 801 TLD Elements Obtained with Manual Reader, Model UD 702A. (a) Lithium-borate Element #2; (b) Calcium-sulfate Element #4. The lithium borate had been exposed to 60 mR and the calcium sulfate to 54 mR of Cobalt-60 gamma radiation.

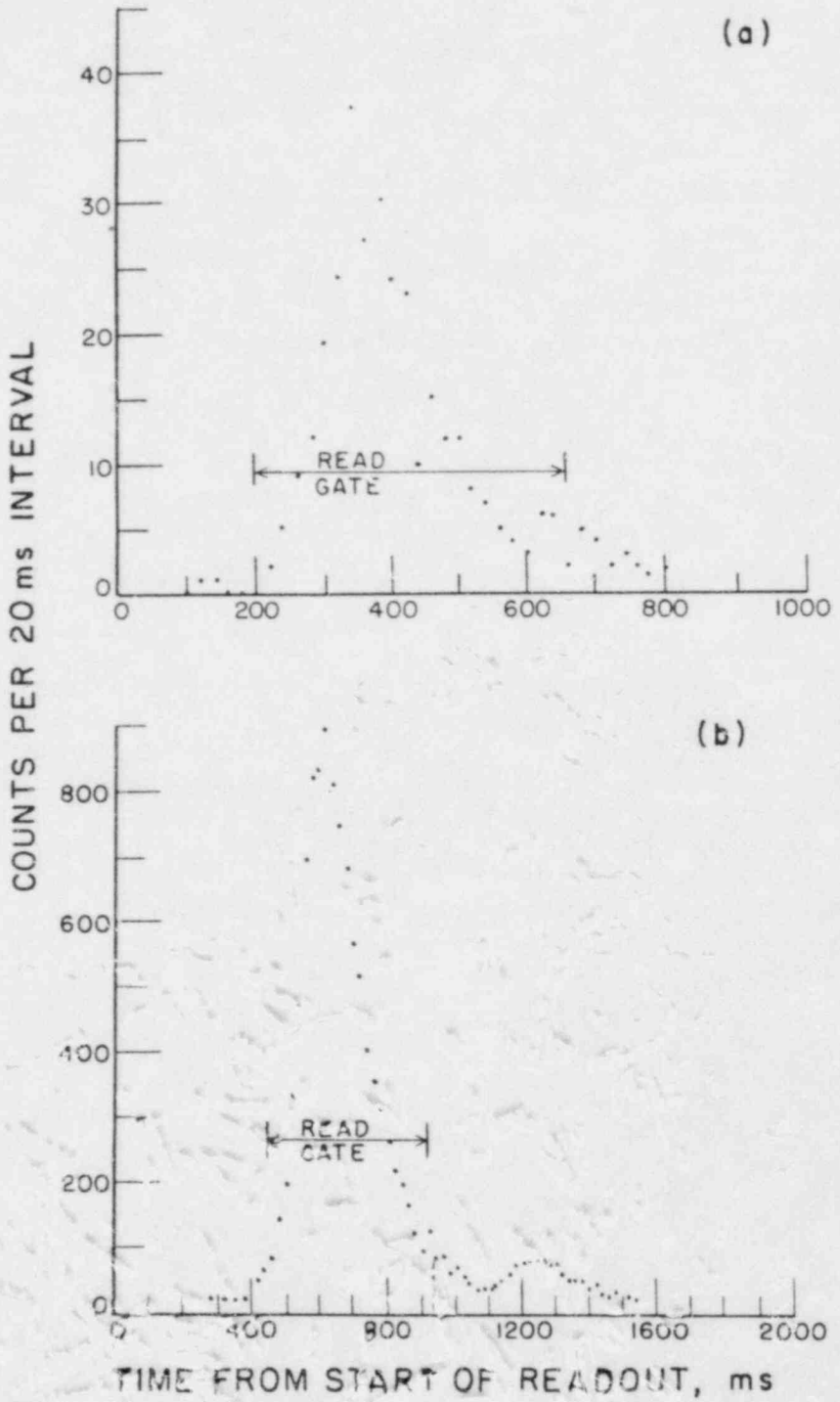


Figure A-4 Glow Curves of UD 801 TLD Elements Obtained with Automatic Reader, Model UD 710A. (a) Lithium-borate Element #1; (b) Calcium-sulfate Element #4. Both elements had been exposed to 130 mR of Cobalt-60 gamma radiation.

The figures demonstrate that in spite of a difference of more than a factor of two in signal-integration time, the shapes of the glow curves are comparable for the particular settings of the two types of readers, and the portions of the glow curves over which the signal is integrated are comparable and adequate. Therefore, it was concluded that the results of the NBS system-characterization studies would also hold for the NRC readout conditions.

4.2 Three-year Follow-up on the Manual Reader

This study encompassed the follow-up of four parameters: (1) the background counting rate of the photomultiplier (the "dark count", checked routinely as part of the "zero check" performed prior to readout of each dosimeter); (2) the counting rate obtained from a short flash of the reader lamp through a small aperture (the "reference-element count", checked routinely as part of the "zero check" performed prior to readout of each dosimeter); (3) the automatic reader-sensitivity adjustment (the "sensitivity correction factor", which takes into account variations in light collection efficiency with reader use and is performed after readout of five dosimeters); and (4) the reproducibility over the three-year period of the response of a set of ten fully characterized dosimeters irradiated at a level corresponding to natural background accumulated during three months.

Figure A-5 shows the results of the study. Averages of twelve successive readings of dark count, reference-element count, and sensitivity-correction factor, selected throughout the three-year period, are plotted as a function of "reader life", measured by the total number of dosimeters read during the three years (a number over 10,000). Shown also are selected sets of averages of the responses obtained from the readings of the calcium-sulfate elements of the ten dosimeters chosen for this follow-up, which had been subjected to a total of 89 readout cycles throughout the three years. The error bars represent the standard deviations of the respective averages.

The average dark counts are seen to have remained fairly constant over the reader life considered, with only one anomalously high average count. This is an indication that there has been no appreciable change in the performance of the photomultiplier or of any pertinent component of the reader electronics. On the other hand, the reference-element counts are seen to decrease monotonically with reader life, the decrease amounting to ~40 percent during the three years. This indicates progressive fatigue of the reader lamp and focusing optics.

The sensitivity correction factor, which is a function of the count rate from a reference light source, is also seen to decrease monotonically, the decrease amounting to between 8 and 10 percent over the three years. The short-term increases, observed after cleaning the infrared filter of the photomultiplier, amounted to at most two percent of the correction factor.

The averages of the dosimeter responses obtained from the readings of the calcium sulfate elements for a selected number of the dosimeters' readout cycles show no trend with reader life, indicating that the automatic reader-sensitivity correction remained adequate over the entire three-year period.

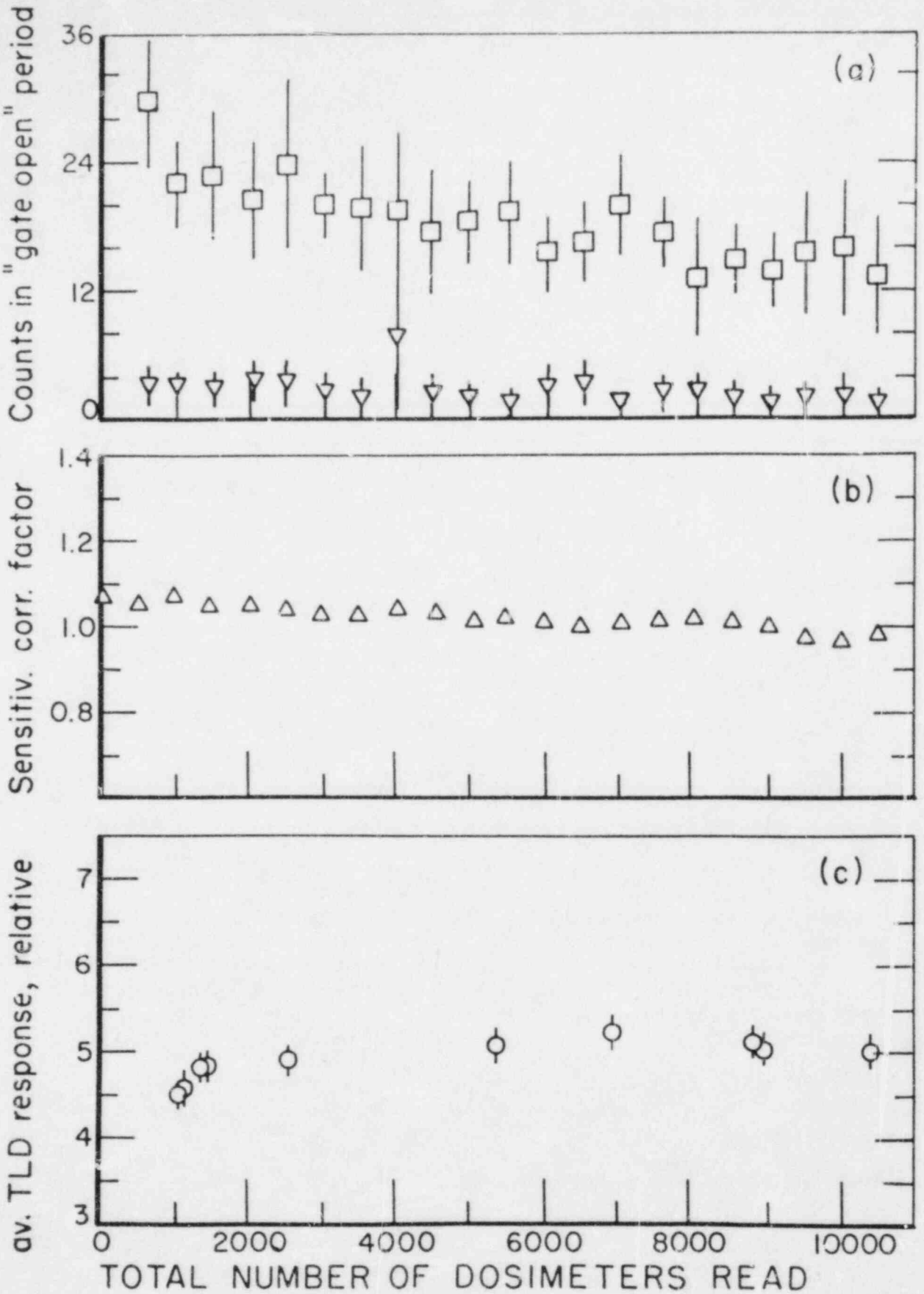


Figure A-5 Three-Year Follow-Up, Manual Reader. (a) Counts during period of open counter gate. Triangles: dark counts; squares: reference element counts. (b) Sensitivity correction factor generated by reader. (c) Average response of the $CaSO_4$:Mn elements of ten selected dosimeters as produced by the reader's automatic correction procedure.

5. Tests by ANSI N545-1975 Specifications as Modified by the NRC and by NBS

In the following, a brief statement of the performance specifications is given for each test, followed by an outline of the procedure and a review of the test results, including a statement of whether or not the two types of dosimeter elements complied with the specifications (i.e., "passed" or "failed"). Where in order, recommendations are made concerning dosimeter application.

5.1 Uniformity (ANSI N545-1975, Section 3.1 and Section 4.3.1)

Performance specifications

TLDs from the same field batch shall be given an exposure equal to that resulting from a 10-μR/h rate during the field cycle (here 3 months). 95 percent of the measurements shall fall within 10 percent of the known exposure (Section 3.1). The relative standard deviation of the responses shall not exceed 7.5 percent (Section 4.3.1).

Procedure

This test was carried out on 90 of the available 300 dosimeters, which were irradiated to 21.6 mR of ^{60}Co gamma radiation, an exposure that is equal to the exposure to which the dosimeters would be subjected during irradiation for a three-months' monitoring period at a rate of 10 μR/h. The evaluation of the readings proceeded under three assumptions on how the NRC laboratory plans to calibrate the dosimeters (or the dosimeter-reader system): (1) each element of each dosimeter characterized individually; (2) reader calibration by average reading on each type of dosimeter element; and (3) reader calibration by average reading on the most reliable dosimeter element(s), say the two calcium sulfate elements. Accordingly, the following quantities were computed: For method (1), the readings on each element corrected according to the element's individual characterization and then averaged; for method (2), the average of the readings referred to the reader calibration for the particular element; and for method (3), the average of the readings referred to the reader calibration for the calcium sulfate elements. Subsequently, the standard deviations from the averages of the readings on the 90 dosimeters and the 95-percent one-sided (upper) confidence intervals on the standard deviations were determined for the three methods, the latter following a procedure given in NBS Handbook 91 [3]. Since, by this procedure, dosimeter readings are referred to exposure, the results can be used to test either according to the performance specifications of Section 3.1 or according to those of Section 4.3.1.

Results

Table A-2 shows the computed averages, relative standard deviations and 95-percent confidence limits for the four elements of the 90 dosimeters determined by the three different calibration methods. When exposure is determined from the response of the lithium-borate elements, the dosimeters are seen to fail the test specifications of Section 3.1 when method 1 is used, but to pass by the other two methods. They are seen to fail the test specifications of Section 4.3.1 by all three methods (at the upper 95% confidence limit). On the other hand, when evaluations are made from the response of the calcium-sulfate elements, the dosimeters pass both tests by all three methods.

Note

The test results indicate that it may be feasible to dispense with time-consuming individual dosimeter-element characterization for many applications to environmental dosimetry, and that, with lithium borate, one may in fact obtain better results with batch calibration since dosimeter-to-dosimeter uniformity of the response in a given batch may be better than the reproducibility of the response of any given dosimeter.

Table A-2. Uniformity of TLD Response

Dosimeter Element	Method 1			Method 2			Method 3		
	Avg.	% SD	% Su	Avg.	% SD	% Su	Avg.	% SD	% Su
$Li_2B_4O_7$:Cu									
element 1	1.0	9.4	10.7	0.98	7.2	8.2	0.9	7.2	8.2
element 2	0.99	8.1	9.2	0.99	7.4	8.4	1.1	7.4	8.4
$CaSO_4$:Tm									
element 3	1.0	2.9	3.3	0.99	5.4	6.2	0.99	5.4	6.2
element 4	1.0	3.0	3.5	0.98	5.6	6.4	0.98	5.6	6.4

Method 1: Individual characterizations
Method 2: Element batch calibration
Method 3: Reader calibration on basis of $CaSO_4$ only

Avg. -- average (mean)
% SD -- relative standard deviation from average (in percent)
% Su -- upper 95% confidence limit on % SD

5.2 Reproducibility (ANSI N545-1975, Section 4.3.2)

Performance specifications

The relative standard deviation of the individual responses from the average response of one TLD given repeated exposures equal to that resulting from a 10-μR/h rate during the field cycle shall not exceed three percent.

Procedure

Fifteen dosimeters were used for 14 cycles of exposures to 21.6 mR of ^{60}Co gamma radiation and subsequent readout on a controlled schedule designed to eliminate the necessity for fading corrections. Subsequently, the following quantities were computed for each element of the fifteen dosimeters: the average response; the standard deviation from the mean of the 14 readings; the relative standard deviation; the percent deviation (range); and the 95-percent one-sided (upper) confidence interval on the relative standard deviation, computed as in 5.1.

Results

Tables A-3a and A-3b show the results, including the actual readings obtained and the computed quantities. When response is determined from the response of the lithium-borate elements, all 15 dosimeters are seen to fail the test (standard deviation larger than 3% at the upper 95% confidence limit). When response is determined from the average readings of the calcium-sulfate elements, the 15 dosimeters are seen to pass the test.

Recommendation

Where good reproducibility is required for readings at levels close to natural background, one should not rely on the lithium-borate elements. However, there are indications that their reproducibility is adequate at higher exposure levels.

5.3 Dependence of Exposure Interpretation on the Length of the Field Cycle (ANSI N545-1975, Section 4.3.3)

Performance specifications

At ambient temperatures, the ratio of the response obtained for the field cycle to twice that obtained for one-half of the field cycle shall not be less than 0.90 when the dosimeters are placed in an area in which the field exposure rate is known to be constant. For extremes of high and low temperatures the corresponding ratios shall not be less than 0.85.

Procedure

(a) At Ambient Temperatures

Twenty dosimeters were placed in an area of the laboratory in which the exposure rate, the temperature, and the relative humidity were monitored periodically, and were expected to remain nearly constant. Ten of the dosimeters were read out midway through the three-month field cycle and again at the end of the field cycle; the other 10 were read out only after the full cycle. Following the readout, averages of the readings and standard deviations from the averages were formed; the ratios of the average readings of each type of dosimeter element for the full field cycle to twice that for one-half of the field cycle were computed and the 95-percent confidence limits determined for these ratios [4].

(b) At Temperatures Other Than Ambient

For the work at ~-20°C and ~+50°C, five different environments were created at each temperature by placing small amounts of saturated salt solutions in the bottom of sealable jars. The salts were chosen so as to produce, in the gas phase above the saturated solutions, air of relative humidities characteristic for the particular salts and temperatures, once the liquid and gas phases were in equilibrium [5,6].

Table A-3a. Reproducibility of Lithium Borate Response

Response, Element 1

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	AVG	SD	%SD	%SP	%Su
1	23.7	25.4	24.0	24.4	23.3	24.9	23.2	21.6	24.3	25.3	21.9	22.9	27.2	24.6	24.05	1.47	6.10	23.37	9.07
2	20.3	19.8	22.4	20.1	21.8	21.0	20.3	20.9	20.4	21.2	19.7	20.9	22.7	20.5	20.86	0.91	4.38	14.38	6.51
3	25.5	20.3	22.6	23.6	21.0	20.9	21.9	21.8	19.8	22.5	22.7	22.4	21.1	19.4	21.82	1.60	7.32	27.95	10.87
4	23.1	21.5	18.7	21.0	24.7	21.8	22.6	22.9	22.0	20.5	24.1	20.4	19.4	20.8	21.68	1.71	7.87	27.72	11.68
5	25.5	23.6	22.1	24.4	24.1	21.3	21.6	22.1	24.2	23.5	22.1	22.6	20.0	20.2	22.66	1.62	7.16	24.27	10.63
6	21.5	23.2	24.9	21.5	23.0	22.3	22.4	23.4	19.8	22.0	20.3	20.5	20.1	24.7	22.11	1.62	7.33	23.07	10.88
7	25.5	20.8	24.1	24.4	22.0	23.2	24.3	25.8	22.4	21.7	24.8	25.1	24.0	22.8	23.64	1.51	6.38	20.97	9.48
8	21.6	22.5	22.4	24.7	23.4	21.9	21.8	22.9	24.1	20.7	24.8	24.0	23.9	23.4	23.00	1.24	5.39	17.82	8.00
9	26.0	20.8	23.7	21.7	22.8	23.2	21.3	21.7	24.5	21.4	23.9	22.7	20.5	24.6	22.77	1.63	7.16	24.16	10.63
10	21.9	24.1	20.6	22.4	18.9	22.2	24.7	21.7	22.3	23.9	20.5	20.7	22.3	20.8	21.92	1.59	7.26	26.61	10.77
11	21.8	23.7	23.8	20.9	23.2	22.5	23.8	21.5	23.4	23.0	22.6	23.3	21.7	21.8	22.63	0.97	4.30	12.82	6.38
12	23.6	22.6	25.4	24.4	22.0	21.4	21.2	21.4	21.8	23.5	19.8	22.5	21.6	22.4	22.40	1.44	6.44	25.00	9.57
13	21.1	23.0	19.2	20.4	20.5	19.5	19.0	22.2	20.3	22.9	22.0	21.2	18.3	19.1	20.62	1.51	7.31	22.79	10.85
14	21.0	22.3	21.5	24.5	22.2	19.9	19.2	22.6	21.3	21.0	21.7	23.8	22.2	23.0	21.87	1.41	6.45	24.23	9.58
15	24.0	20.4	20.1	20.2	20.3	23.4	18.9	19.3	21.1	20.4	21.4	20.3	21.9	21.0	20.91	1.42	6.78	24.39	10.06

Response, Element 2

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	AVG	SD	%SD	%SP	%Su
1	30.3	28.9	28.6	27.6	29.9	31.3	28.8	28.4	25.7	28.6	28.7	29.6	28.8	27.8	28.79	1.32	4.59	19.45	6.82
2	29.2	27.9	27.3	29.0	27.4	24.2	25.2	24.2	29.1	26.5	24.1	25.9	24.9	24.9	26.41	1.91	7.22	19.31	10.72
3	28.6	26.5	24.0	28.4	25.9	28.2	26.7	27.9	26.5	25.7	26.2	27.4	29.9	28.0	27.14	1.50	5.52	21.74	8.20
4	25.1	25.2	23.7	26.1	26.6	24.4	25.7	24.5	27.2	23.5	24.9	27.2	27.7	24.9	25.47	1.32	5.19	16.49	7.71
5	28.9	31.3	28.6	27.2	27.2	28.5	25.5	28.3	27.4	24.6	27.7	29.3	27.0	29.4	27.92	1.68	6.01	24.00	8.92
6	28.7	27.6	27.3	29.8	28.7	29.9	27.6	27.2	27.3	24.9	25.2	28.1	28.8	27.5	27.76	1.45	5.22	18.01	7.75
7	27.6	29.6	25.3	29.5	29.5	27.6	27.8	30.2	29.8	30.0	26.9	28.0	26.5	27.9	28.30	1.50	5.29	17.42	7.86
8	28.8	29.0	30.1	30.4	27.9	29.5	24.9	29.7	26.5	29.2	30.1	30.1	28.0	28.4	28.76	1.55	5.40	19.12	8.01
9	32.6	25.7	26.2	24.9	27.8	27.2	26.3	29.6	31.9	29.3	28.1	26.8	28.8	29.0	28.20	2.20	7.82	27.30	11.61
10	27.6	28.0	27.8	27.9	25.2	26.0	27.8	27.5	28.0	27.7	27.1	26.2	26.8	26.6	27.16	0.87	3.21	10.23	4.77
11	26.1	26.3	26.9	29.1	26.5	28.6	26.8	27.3	27.5	26.9	29.2	26.1	32.8	27.2	27.66	1.80	6.51	24.22	9.67
12	26.4	29.9	30.6	28.9	29.2	29.0	27.5	28.0	30.2	30.9	26.2	29.3	30.3	25.8	28.73	1.69	5.89	17.75	8.75
13	24.9	26.1	26.8	27.9	24.0	26.0	24.5	24.1	27.1	26.1	22.8	22.7	27.8	24.2	25.29	1.76	6.94	20.56	10.31
14	28.2	28.3	24.0	26.3	26.2	26.6	27.8	25.5	26.0	26.7	28.5	24.1	26.0	26.6	26.49	1.40	5.30	16.99	7.86
15	27.2	26.4	27.0	26.7	26.6	25.7	25.4	26.2	24.5	26.3	25.3	24.8	27.7	27.7	26.24	1.00	3.82	12.19	5.68

AVG — average
SD — absolute standard deviation from average
%SD — percent standard deviation from average
%SP — percent deviation from average ("spread")
%Su — upper 95% confidence limit on %SD

Table A-3b. Reproducibility of Calcium Sulfate Response

Response, Element 3 and 4

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	AVG	SD	%SD	%SP	%Su
1	22.9	23.2	24.1	22.9	23.5	23.5	23.0	23.4	23.6	23.6	22.9	23.3	23.5	23.4	23.32	0.33	1.44	5.15	2.13
2	23.5	23.7	24.1	23.7	23.6	23.8	23.3	23.1	24.1	23.8	23.3	23.2	23.3	23.6	23.55	0.33	1.39	4.37	2.06
3	23.9	24.3	24.5	25.2	24.4	24.1	24.6	24.5	24.3	24.7	24.4	24.5	23.9	24.4	24.38	0.33	1.37	5.54	2.03
4	22.5	22.1	22.0	22.4	22.8	22.3	22.8	23.2	23.1	22.5	22.6	22.5	22.7	22.8	22.57	0.35	1.54	5.41	2.28
5	24.1	23.1	24.3	24.2	23.8	24.0	24.1	23.4	24.2	24.1	24.3	23.7	24.0	24.5	23.95	0.38	1.60	6.05	2.37
6	25.6	25.3	25.6	26.0	24.8	25.6	25.3	25.7	25.9	26.3	25.5	25.8	25.9	25.7	25.62	0.37	1.42	6.01	2.12
7	23.1	23.4	22.9	22.7	23.0	22.9	22.9	22.4	22.7	23.3	23.8	23.0	22.3	22.8	22.92	0.38	1.68	6.54	2.49
8	25.3	24.9	24.2	25.0	24.2	24.0	24.4	25.1	24.9	24.7	24.6	24.1	24.8	24.4	24.60	0.40	1.61	5.08	2.39
9	25.9	26.5	25.8	26.1	26.1	25.4	26.1	26.6	25.4	25.6	26.5	26.0	26.0	26.0	25.98	0.37	1.42	4.43	2.11
10	23.4	23.7	23.0	23.5	23.7	23.1	23.6	23.4	23.6	23.5	23.3	23.8	23.8	23.9	23.50	0.27	1.14	3.83	1.69
11	23.5	23.2	22.8	22.9	22.8	23.3	23.2	23.2	23.3	23.1	22.6	23.1	22.9	23.1	23.05	0.24	1.05	3.90	1.57
12	25.6	24.9	25.4	25.5	25.1	24.5	25.3	25.1	24.6	25.0	24.9	26.1	25.3	24.6	25.13	0.44	1.76	6.37	2.61
13	21.5	21.4	21.9	20.9	21.3	22.1	21.5	21.7	21.4	21.5	21.4	21.7	20.9	21.6	21.48	0.32	1.50	5.35	2.23
14	23.7	23.4	23.8	23.6	23.6	23.5	23.3	24.0	23.4	23.7	22.9	23.6	23.3	23.7	23.52	0.27	1.14	4.75	1.69
15	24.3	24.5	24.0	24.2	24.1	24.5	24.3	23.9	24.0	24.2	24.1	24.5	23.5	23.9	24.12	0.29	1.22	4.35	1.81

AVG — average
SD — absolute standard deviation from average
%SD — percent standard deviation from average
%SP — percent deviation from average ("spread")
%Su — upper 95% confidence limit on %SD

A set of 20 sealed jars, each containing five individually calibrated dosimeters, individually sealed in plastic bags and suspended above the fluid level, was stored in a freezer at ~-20°C. Another set of 20 sealed jars, each containing four similarly prepared dosimeters, was stored in an oven at ~+50°C. Halfway through the three-month cycle, two each of the four jars maintained at the same relative humidity were brought back to laboratory temperature, the dosimeters contained therein were removed, read out, and then returned to the jars. The jars subsequently were resealed and returned to their original extreme temperatures. At the end of three months, all jars were brought back to room temperature and all test dosimeters were read out.

For the test at ~-40°C, no attempt was made to maintain environments of different relative humidities. Twenty dosimeters, each sealed in a plastic bag, were suspended freely in a freezer and kept there for three months. Half-way through the three-month cycle, 10 of them were briefly removed for readout and then returned to the freezer. At the end of the three months, all 20 dosimeters were read out.

Results

The 95-percent confidence limits on the ratios are shown in Tables A-4 through A-7, as obtained from the readings of the two lithium-borate elements separately, and from the combined readings of the two calcium-sulfate elements. The results are reviewed in Table A-8. The dosimeters are seen to pass all the tests when response is evaluated from the average readings of the calcium-sulfate elements. When the evaluation is made from the readings of the lithium-borate elements, the dosimeters generally fail. In fact, at the highest test temperature (~+50°C) and a relative humidity of 98 percent, at which the lithium-borate elements were found to be damaged through liquefaction, the readings of the lithium-borate elements are essentially obliterated (see Table A-7). The failure becomes less prevalent with decreasing levels of relative humidity.

5.4 Energy Dependence (ANSI N545-1975, Section 4.3.4)

Performance specifications

For photon energies in the range 80 keV $\leq$ E $\leq$ 3 MeV, the ratio of the TLD response to photons of energy E to that of photons of the calibration source shall not be smaller than 0.80 nor larger than 1.20; for photon energies in the range 30 keV $\leq$ E $<$ 80 keV, it shall not be larger than 2.00.

Procedure

Eight photon beams of different qualities were employed: the five heavily-filtered NBS standard bremsstrahlung beams described in NBS Technical Publication 250 [7], (excerpted from that publication in Table A-9), a 3-MV bremsstrahlung beam filtered through ~2.5 cm of lead, and two gamma-ray beams from the radionuclides ^{137}Cs and ^{60}Co. At each beam quality, three exposure levels between ~50 and ~200 mR (all in the linear range of the TLD's response curves) were used, except for the 300-MV bremsstrahlung beam, for which irradiation was administered at two levels between ~250 and 500 mR. Two dosimeters were exposed at each level. From the resulting response data, response per

unit exposure was obtained. (Where required, individual recalibrations with ^{60}Co gamma radiation were performed. The adopted readout schedule--see Section 3.3--permitted us to ascertain that, at the higher exposure levels, there were indeed residual filled traps left after the initial exposure readouts. They were emptied by the second readout.)

Table A-4. Dependence of Exposure Interpretation on Length of Field Cycle at Ambient Temperatures and Relative Humidities

	AVERAGE READINGS		
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm elements
	1	2	3 and 4 combined
	84% rel. hum. (NH_4Cl)		
Readout after:			
1st half-cycle	0.22 ± 0.04	0.17 ± 0.04	0.25 ± 0.03
2nd half-cycle	0.26 ± 0.05	0.21 ± 0.05	0.28 ± 0.03
Both half cycles (avg.)	0.24 ± 0.05	0.19 ± 0.05	0.26 ± 0.03
Whole cycle	0.46 ± 0.06	0.34 ± 0.08	0.57 ± 0.02
Ratio, both half-cycles (avg.) to whole-cycle readings	0.96 ± 0.23	0.90 ± 0.31	1.08 ± 0.14
95% confidence limit on ratio	±0.13	±0.18	±0.08

Results

The results of the study are shown in Table A-10, where the average values of the response ratios derived from the readings on six dosimeters, the standard deviations, and the 95-percent confidence intervals on the averages (computed as in 5.2) are given. In the energy range 80 keV < E < 1.25 MeV, the dosimeters pass the test when response is determined from the readings of the lithium-borate elements under their respective filters, while they fail when it is determined from the readings of the calcium-sulfate elements (under lead). On the other hand, for 3-MV filtered bremsstrahlung, the dosimeters pass when response is determined from the readings of the calcium-sulfate elements (under lead) but not when it is determined from the lithium-borate elements, where lack of build-up material required to establish a condition close to electron equilibrium is particularly pronounced. Below 80 keV, the dosimeters pass when response is determined from the readings of either element of both types of phosphor.

Recommendation

The filtration of the calcium-sulfate elements should be replaced by filtration resulting in less attenuation of the incident radiation.

Table A-5. Dependence of Exposure Interpretation on Length of Field Cycle at ~20°C

	AVERAGE READINGS		
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm elements
	#1	#2	#3 and #4 combined
	(a) 84% rel. hum. (NH_4Cl)		
Readout after:			
1st half-cycle	0.30 ± 0.04	0.18 ± 0.05	0.31 ± 0.02
2nd half-cycle	0.25 ± 0.07	0.15 ± 0.03	0.30 ± 0.01
Both half cycles (avg.)	0.27 ± 0.06	0.17 ± 0.04	0.31 ± 0.02
Whole cycle	0.60 ± 0.08	0.40 ± 0.05	0.62 ± 0.04
Ratio, both half-cycle (avg.) to whole-cycle readings	1.10 ± 0.29	1.19 ± 0.35	1.02 ± 0.08
95% confidence limit on ratio	±0.21	±0.25	±0.06
	(b) 72% rel. hum. ($Ca(NO_3)_2$)		
Readout after:			
1st half-cycle	0.31 ± 0.06	0.18 ± 0.03	0.32 ± 0.01
2nd half-cycle	0.22 ± 0.03	0.14 ± 0.03	0.30 ± 0.01
Both half cycles (avg.)	0.27 ± 0.07	0.16 ± 0.04	0.31 ± 0.02
Whole cycle	0.64 ± 0.09	0.34 ± 0.05	0.65 ± 0.02
Ratio, both half-cycle (avg.) to whole-cycle readings	1.19 ± 0.33	1.04 ± 0.27	1.04 ± 0.06
95% confidence limit on ratio	±0.24	±0.20	±0.04
	(c) 68% rel. hum. ($CuCl_2$)		
Readout after:			
1st half-cycle	0.29 ± 0.07	0.18 ± 0.02	0.32 ± 0.01
2nd half-cycle	0.28 ± 0.05	0.16 ± 0.04	0.30 ± 0.01
Both half cycles (avg.)	0.28 ± 0.06	0.17 ± 0.04	0.31 ± 0.01
Whole cycle	0.59 ± 0.06	0.36 ± 0.04	0.63 ± 0.03
Ratio, both half-cycle (avg.) to whole-cycle readings	1.05 ± 0.24	1.04 ± 0.24	1.00 ± 0.06
95% confidence limit on ratio	±0.17	±0.17	±0.05

Table A-5 (Continued). Dependence of Exposure Interpretation on Length of Field Cycle at ~20°C

	AVERAGE READINGS		
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm elements
	#1	#2	#3 and #4 combined
	(d) 33% rel. hum. ($MgCl_2$)		
Readout after:			
1st half-cycle	0.31 ± 0.05	0.18 ± 0.04	0.32 ± 0.02
2nd half-cycle	0.26 ± 0.07	0.15 ± 0.03	0.30 ± 0.02
Both half cycles (avg.)	0.29 ± 0.06	0.16 ± 0.04	0.31 ± 0.02
Whole cycle	0.61 ± 0.04	0.36 ± 0.04	0.64 ± 0.02
Ratio, both half-cycle (avg.) to whole-cycle readings	1.06 ± 0.25	1.11 ± 0.28	1.05 ± 0.08
95% confidence limit on ratio	±0.18	±0.20	±0.06
	(e) 18% rel. hum. (LiCl)		
Readout after:			
1st half-cycle	0.28 ± 0.07	0.19 ± 0.04	0.31 ± 0.02
2nd half-cycle	0.34 ± 0.21	0.15 ± 0.03	0.29 ± 0.02
Both half cycles (avg.)	0.31 ± 0.15	0.17 ± 0.04	0.30 ± 0.02
Whole cycle	0.56 ± 0.09	0.34 ± 0.03	0.64 ± 0.04
Ratio, both half-cycle (avg.) to whole-cycle readings	0.90 ± 0.47	1.00 ± 0.24	1.06 ± 0.09
95% confidence limit on ratio	±0.33	±0.17	±0.06

Table A-6. Dependence of Exposure Interpretation on Length of Field Cycle at ~-40°C

	AVERAGE READINGS		
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm elements
	#1	#2	#3 and #4 combined
Readout after:			
1st half-cycle	0.27 ± 0.06	0.19 ± 0.06	0.33 ± 0.03
2nd half-cycle	0.23 ± 0.05	0.17 ± 0.05	0.30 ± 0.02
Both half cycles (avg.)	0.25 ± 0.06	0.18 ± 0.05	0.31 ± 0.03
Whole cycle	0.49 ± 0.08	0.35 ± 0.04	0.62 ± 0.05
Ratio, both half-cycles (avg.) to whole-cycle readings	0.98 ± 0.27	0.95 ± 0.30	0.98 ± 0.12
95% confidence limit on ratio	±0.19	±0.21	±0.09

5.5 Directional Dependence (ANSI N545-1975, Section 4.3.5)

Performance specifications

When the dosimeter is rotated about two axes perpendicular to each other, the ratio of the response averaged over all directions to the response obtained in the usual calibration orientation shall be not less than 0.90 and not more than 1.10.

Procedure

This experiment was performed with four different dosimeter supports:

- Bare dosimeter with low-scatter support;
- Dosimeter in plastic bag, taped directly against a wooden utility pole;
- Dosimeter in plastic bag, in plastic mesh cage, with cage taped against the utility pole;
- Dosimeter in plastic bag, taped to a 30.5-cm Al spoke, which in turn was fastened against the ~25-cm-diameter pole.

Table A-7. Dependence of Exposure Interpretation on Length of Field Cycle at ~+50°C

	AVERAGE READINGS		
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm elements
	#1	#2	#3 and #4 combined
	(a) 98% rel. hum. (H_2O)		
Readout after:			
1st half-cycle	-0.02 ± 0.02	-0.01 ± 0.01	0.28 ± 0.02
2nd half-cycle	-0.01 ± 0.02	-0.01 ± 0.01	0.25 ± 0.01
Both half cycles (avg.)	-0.01 ± 0.02	-0.01 ± 0.01	0.26 ± 0.02
Whole cycle	-0.08 ± 0.16	-0.01 ± 0.02	0.51 ± 0.04
Ratio, both half-cycle (avg.) to whole-cycle readings	2.65 ± 6.49	0.56 ± 1.31	0.97 ± 0.10
95% confidence limit on ratio	±4.64	±0.93	±0.07
	(b) 75% rel. hum. (NaCl)		
Readout after:			
1st half-cycle	0.39 ± 0.06	0.24 ± 0.06	0.29 ± 0.01
2nd half-cycle	0.36 ± 0.06	0.20 ± 0.05	0.26 ± 0.01
Both half cycles (avg.)	0.38 ± 0.06	0.22 ± 0.06	0.27 ± 0.02
Whole cycle	0.68 ± 0.11	0.41 ± 0.09	0.56 ± 0.02
Ratio, both half-cycle (avg.) to whole-cycle readings	0.91 ± 0.21	0.94 ± 0.31	1.04 ± 0.08
95% confidence limit on ratio	±0.15	±0.22	±0.05
	(c) 47% rel. hum. (Na_2CrO_7)		
Readout after:			
1st half-cycle	0.45 ± 0.04	0.31 ± 0.06	0.29 ± 0.01
2nd half-cycle	0.39 ± 0.07	0.28 ± 0.07	0.27 ± 0.01
Both half cycles (avg.)	0.42 ± 0.06	0.30 ± 0.07	0.28 ± 0.02
Whole cycle	0.78 ± 0.08	0.47 ± 0.12	0.57 ± 0.02
Ratio, both half-cycle (avg.) to whole-cycle readings	0.94 ± 0.17	0.79 ± 0.27	1.02 ± 0.07
95% confidence limit on ratio	±0.12	±0.19	±0.05

Table A-7 (Continued). Dependence of Exposure Interpretation on Length of Field Cycle at ~+50°C

	AVERAGE READINGS		
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm elements
	#1	#2	#3 and #4 combined
	(d) 31% rel. hum. ($MgCl_2$)		
Readout after:			
1st half-cycle	0.42 ± 0.05	0.28 ± 0.05	0.29 ± 0.01
2nd half-cycle	0.36 ± 0.03	0.26 ± 0.07	0.27 ± 0.01
Both half cycles (avg.)	0.39 ± 0.05	0.27 ± 0.06	0.28 ± 0.01
Whole cycle	0.76 ± 0.08	0.43 ± 0.07	0.58 ± 0.02
Ratio, both half-cycle (avg.) to whole-cycle readings	0.97 ± 0.16	0.80 ± 0.22	1.03 ± 0.07
95% confidence limit on ratio	±0.11	±0.08	±0.05
	(e) 11% rel. hum. (LiCl)		
Readout after:			
1st half-cycle	0.45 ± 0.11	0.28 ± 0.07	0.29 ± 0.02
2nd half-cycle	0.38 ± 0.08	0.23 ± 0.05	0.27 ± 0.02
Both half cycles (avg.)	0.42 ± 0.10	0.25 ± 0.06	0.28 ± 0.02
Whole cycle	0.86 ± 0.07	0.47 ± 0.09	0.58 ± 0.02
Ratio, both half-cycle (avg.) to whole-cycle readings	1.03 ± 0.26	0.92 ± 0.28	1.04 ± 0.08
95% confidence limit on ratio	±0.19	±0.20	±0.06

Four individually calibrated dosimeters were used for each point in each of the four geometries. The dosimeters were irradiated while rotating continuously.* In the low-scatter geometry, the speed of rotation was ~140 rpm. In the other three geometries, the speed was exactly 2.0 rpm, with the irradiation starting at perpendicular radiation incidence upon the front of the dosimeter and continuing for exactly six revolutions. Two axes of rotation, perpendicular to each other and passing through the sensitive dosimeter volume either parallel to the long or to the short symmetry axis of the dosimeter, were used in the low-scatter geometry; one axis, parallel to the long symmetry axis of the dosimeter, was used in the geometries involving the utility pole.

*The dosimeters also were irradiated in eight fixed orientations (see Section 6). However, the results of that study cannot be used to test for performance by the specifications of ANSI N545-1975.

Table A-8. Summary, Results of Environmental Tests
(ANSI N545-1975, Section 4.3.3, Dependence of
Dosimeter Response on the Length of the Field Cycle,
and ANSI N545-1975, Section 4.3.7, Moisture Dependence)

Environmental Conditions		Test Results* for Evaluation from Readings of		
		$Li_2B_4O_7$:Cu		$CaSO_4$:Tm
Temperature °C	Relative Humidity %	element #1	element #2	both elements
~-40	ambient (in freezer)	F	F	P
~-20	84	P	P	P
"	72	P	F	P
"	68	P	P	P
"	33	P	P	P
"	18	F	F	P
room	ambient (in laboratory)	F	F	P
room	100	F	F	P
~+50	98	F	F	P
"	75	F	F	P
"	47	F	F	P
"	31	P	F	P
"	11	F	F	P

*P - pass (ratio of twice the response for one-half of field cycle and response for whole field cycle ≥0.90 at room temperature and ≥0.85 at other temperatures, when evaluated on the 95% confidence level)

*F - fail (ratio of twice the response for one-half of field cycle and response for whole field cycle <0.90 at room temperature and <0.85 at other temperatures, when evaluated on the 95% confidence level)

The distance from the source to the dosimeters was ~2 m at all times. Exposure levels were usually in the vicinity of 120 mR. In one instance an exposure level of ~21.6 mR, corresponding to 10 μR/h for three months, was used. The source-to-pole distance--and therefore the exposure rate at the pole--varied during each dosimeter revolution.* However, an inspection of the data for support geometries with and without pole showed that the effect did not cause a change (decrease) of the relative response by more than 3 percent.

*This is inevitable because (1) the distance between the source and the dosimeter is kept constant and (2) the available source-to-dosimeter distance is limited. The result is a distance-dependent modification of the dependence of the pole-scatter contribution to dosimeter response on the angle of radiation incidence.

Table A-9. NBS Bremsstrahlung Beams Used for Energy Dependence Study

HEAVILY FILTERED X RAYS											
Beam Code Designation		Constant Potential	Added Filter*				Half-Value Layer		Effective	Exposure Rate	
Old	New	kV	Pb mm	Sn mm	Cu mm	Al mm	Cu mm	Al mm	Energy keV	Min. mR/s	Max. mR/s
HFC	H50	50	0.10	0	0	2.50	0.14	4.19	38	0.3	1.5
HFE	---	100	0.50	0	0	2.50	0.74	11.20	70	0.8	4
HFG	H150	150	0	1.51	4.00	2.50	2.45	16.96	117	0.7	4
HFI	H200	200	0.77	4.16	0.60	2.47	4.09	19.60	167	0.5	4
HFK	H250	250	2.72	1.04	0.60	2.50	5.25	21.55	210	0.5	4

*The inherent filtration is approximately 1.5 mm Al.

(a) Results for bare dosimeters with low-scatter support

Table A-11 shows the range of response values corresponding to a 95-percent confidence interval for dosimeter rotation around both axes of rotation over the range of photon energies from 38 keV to 1250 keV, and also includes a sketch illustrating the direction of irradiation relative to the axes of rotation.

For rotation about the major axis, the dosimeters are seen to meet the requirements at all photon energies when response is obtained from the readings of the lithium-borate elements (although the performance is marginal at 38 keV for element 1). They fail below 167 keV when the response is obtained with calcium sulfate.

For rotation about the minor axis, the dosimeters fail to meet the requirements over the entire range of energies tested, except when response is obtained from the readings of lithium-borate element 1. (Even then, performance is only marginal at 38 keV.) When lithium-borate element 2 is used, dosimeter performance is adequate only at 1250 keV.

When calcium sulfate is used to obtain dosimeter response, the dosimeters fail at 38 keV, 70 keV, and 117 keV; their performance is marginal at 167 keV, and they clearly pass only for 210 keV, 662 keV, and 1250 keV.

Note: Performance at energies in the range 1250 keV $\leq$ E $\leq$ 3000 keV is expected to be similar to that at 1250 keV.

(b) Results for dosimeters in plastic bags, hung from a wooden pole in three different ways.

Table A-12 shows the range of response values obtained in the three different geometries (dosimeters in a plastic "cage"; dosimeters taped to a spoke fastened to the pole; dosimeters directly attached to the pole). The major axis of the dosimeters was made parallel to the axis of the pole. Because of the presence of the pole, it was impossible to use a second axis of rotation as long as the dosimeter orientation relative to the pole had to remain fixed.

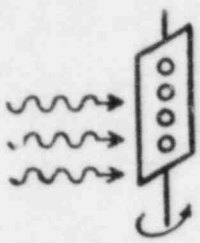
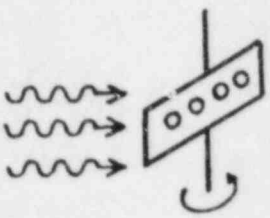
Table A-10. Response per Unit Exposure Relative to that for ^{60}Co Gamma Radiation

Beam Quality	$Li_2B_4O_7$:Cu under plastic of thickness: 14 mg/cm² element 1			300 mg/cm² element 2		
	Avg.	S	Conf. Lim.	Avg.	S	Conf. Lim.
Effective Energy (keV):						
38	0.90	0.10	0.10	0.76	0.05	0.06
70	0.98	0.09	0.10	0.85	0.05	0.05
117	0.98	0.07	0.08	0.88	0.07	0.08
167	1.09	0.11	0.12	0.91	0.07	0.07
210	1.11	0.08	0.08	0.97	0.08	0.08
662	1.13	0.08	0.08	1.03	0.07	0.07
1250	1.00	0.09	0.09	1.00	0.07	0.07
3 MV bremsstrahlung, filtration: ~2.5 cm Pb	0.71	0.05	0.04	0.79	0.05	0.03

	$CaSO_4$:Tm under 700 mg/cm² of lead element 3			element 4		
	Avg.	S	Conf. Lim.	Avg.	S	Conf. Lim.
Effective Energy (keV):						
38	0.44	0.01	0.01	0.45	0.02	0.02
70	0.91	0.02	0.02	0.92	0.04	0.04
117	0.63	0.01	0.01	0.62	0.03	0.03
167	0.81	0.02	0.02	0.80	0.02	0.03
210	0.91	0.02	0.02	0.89	0.02	0.02
662	1.14	0.02	0.02	1.13	0.04	0.04
1250	1.00	0.01	0.01	1.00	0.03	0.03
3 MV bremsstrahlung, filtration: ~2.5 cm Pb	0.88	0.05	0.04	0.88	0.05	0.04

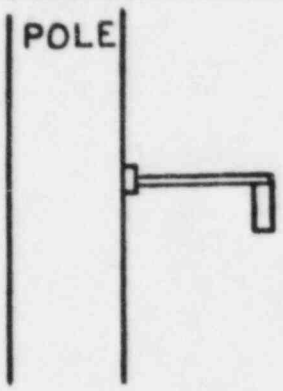
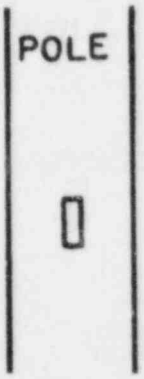
Avg. -- average (mean)
S -- ± standard deviation from average
Conf. Lim. -- ±95% confidence limit on average

Table A-11. Directional Dependence of Dosimeter Response for Continuous Dosimeter Rotation with Bare Dosimeters and Low-Scatter Support

Effective Energy	Response* relative to that for perpendicular radiation incidence for the following geometries:			
				
	Rotation about major axis (vertical)		Rotation about minor axis (horizontal)	
	Element 1	Element 2	Element 1	Element 2
38 keV	0.94 ± 0.05*	0.99 ± 0.06	0.92 ± 0.06	0.84 ± 0.04
70 keV	1.01 ± 0.04	1.00 ± 0.06	0.96 ± 0.05	0.87 ± 0.05
117 keV	0.97 ± 0.04	1.03 ± 0.05	0.95 ± 0.06	0.88 ± 0.05
167 keV	1.01 ± 0.05	0.97 ± 0.04	0.96 ± 0.05	0.89 ± 0.04
210 keV	0.96 ± 0.04	0.97 ± 0.04	0.95 ± 0.03	0.90 ± 0.03
662 keV	0.98 ± 0.05	0.95 ± 0.04	0.94 ± 0.04	0.94 ± 0.05
1250 keV	1.01 ± 0.04	1.00 ± 0.04	0.96 ± 0.05	0.95 ± 0.04
	Element 3	Element 4	Element 3	Element 4
38 keV	8.16 ± 0.25	6.64 ± 0.17	6.08 ± 0.17	6.87 ± 0.18
70 keV	1.86 ± 0.04	1.84 ± 0.03	1.66 ± 0.04	1.76 ± 0.06
117 keV	1.60 ± 0.03	1.62 ± 0.03	1.42 ± 0.02	1.50 ± 0.05
167 keV	1.06 ± 0.02	1.06 ± 0.02	1.00 ± 0.02	1.02 ± 0.02
210 keV	0.96 ± 0.01	0.96 ± 0.02	0.93 ± 0.02	0.96 ± 0.02
662 keV	0.93 ± 0.02	0.93 ± 0.01	0.95 ± 0.01	0.93 ± 0.02
1250 keV	1.06 ± 0.02	1.06 ± 0.04	1.04 ± 0.02	1.04 ± 0.02

*The range of values shown corresponds to a ±95 percent confidence interval.

Table A-12. Directional Dependence of Dosimeter Response for Continuous Dosimeter Rotation with Dosimeters Hung on a Wooden Utility Pole in Three Different Ways

Element number and effective photon energy	Response* relative to that for perpendicular radiation incidence, for the following geometries (side view)**:		
	 Dosimeter in cage hung on pole	 Dosimeter taped to a 30.5-cm Al spoke	 Dosimeter attached directly to pole
Element 1			
38 keV	0.72 ± 0.05	0.86 ± 0.04	0.62 ± 0.05
117 keV	0.79 ± 0.04	0.90 ± 0.05	0.71 ± 0.03
210 keV	0.80 ± 0.03	0.94 ± 0.06	0.75 ± 0.04
1250 keV	0.87 ± 0.11	0.94 ± 0.10	0.93 ± 0.12
Element 2			
38 keV	0.70 ± 0.05	0.92 ± 0.06	0.63 ± 0.04
117 keV	76 ± 0.03	0.90 ± 0.05	0.70 ± 0.04
210 keV	0.79 ± 0.04	0.92 ± 0.04	0.73 ± 0.03
1250 keV	0.89 ± 0.07	0.92 ± 0.11	0.90 ± 0.07
Element 3			
38 keV	3.69 ± 0.26	3.33 ± 0.10	2.78 ± 0.18
117 keV	1.26 ± 0.04	1.29 ± 0.02	1.13 ± 0.04
210 keV	0.85 ± 0.01	0.92 ± 0.01	0.78 ± 0.01
1250 keV	0.94 ± 0.03	1.00 ± 0.02	0.90 ± 0.03
Element 4			
38 keV	3.23 ± 0.13	2.98 ± 0.12	2.39 ± 0.08
117 keV	1.23 ± 0.03	1.27 ± 0.03	1.10 ± 0.03
210 keV	0.84 ± 0.01	0.93 ± 0.02	0.79 ± 0.01
1250 keV	0.93 ± 0.03	1.01 ± 0.03	0.90 ± 0.04

*The range of values shown correspond to a ±95 percent confidence interval.

**Beam incident perpendicularly to page. Dosimeter and holder shown for pole orientation for which beam is incident perpendicularly to front of dosimeter.

The spoke geometry, on the average, is seen to produce a material improvement in dosimeter performance over the plastic-cage geometry, which, in turn, produces a better performance than the dosimeters hung directly on the pole. Nevertheless, the dosimeters are seen to pass only for ^{60}Co gamma radiation, and then unequivocally only when the response is determined from the calcium sulfate elements of dosimeters in the cage or suspended from the spoke.

Note: Response at photon energies in the range 1250 keV < E ≤ 3000 keV is expected to be similar to that at 1250 keV.

Recommendation

The response of the calcium-sulfate elements could be materially improved through judicious lateral shielding by a high-atomic number material (lead, tungsten) incorporated into the holder (say, in the form of a sleeve around the phosphor support, taking the place of the present brass sleeve).

5.6 Light Dependence (ANSI N545-1975, Section 4.3.6)

Performance specifications

The ratio of the net response of dosimeters to a 100-mR irradiation above background, for dosimeters stored bare in the field over a period of one field cycle, to that of identically irradiated dosimeters stored wrapped in household aluminum foil, shall not be smaller than 0.90 or larger than 1.10.

Procedure

A batch of 20 dosimeters was used for this experiment, 10 irradiated to 100 mR of ^{60}Co gamma radiation, 10 left unirradiated. Five each of the irradiated and of the unirradiated dosimeters were wrapped in household aluminum foil, the other five were left bare. All dosimeters were sealed in plastic bags supplied by the NRC Region 1 laboratory (10 dosimeters per bag) and the bags were hung in an open off-site field, so that the dosimeters were in a vertical north-south orientation, facing south. After 1 1/2 months (i.e., in the middle of the field cycle), the bags were rotated so that the badge orientation was reversed. At the end of the field cycle, all dosimeters were read out; the averages and the readings of the dosimeter elements not initially irradiated in the laboratory were subtracted from those of the irradiated elements; for each of the two irradiation conditions, the ratios were formed of these differences, for the dosimeters stored bare divided by those for the dosimeters stored wrapped in aluminum, and the 95-percent confidence limits on these ratios were computed, as in 5.3.

Results

Table A-13 shows the averages of the five readings and the standard deviations from these averages obtained for each type of dosimeter element and for each of the four different conditions of handling of the dosimeters. Further shown are the ratios of the net averages for the unwrapped and the wrapped dosimeters, and the standard deviations and 95-percent confidence limits on these ratios. When response is determined with the lithium-borate elements, the dosimeters fail the test. They pass when response is determined with the calcium-sulfate elements.

Table A-13. Light Dependence of TLD Response

	RESPONSE			
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm element	
	1	2	3	4
Conditions:				
Unexposed, unwrapped	1.73 ± 0.05	1.17 ± 0.15	1.35 ± 0.05	1.35 ± 0.05
Unexposed, wrapped	1.54 ± 0.05	1.12 ± 0.05	1.32 ± 0.06	1.36 ± 0.09
Exposed, unwrapped	4.43 ± 0.26	4.68 ± 0.22	5.50 ± 0.12	5.55 ± 0.12
Exposed, wrapped	5.60 ± 0.36	5.00 ± 0.13	5.64 ± 0.11	5.71 ± 0.04
Difference, unwrapped	2.70 ± 0.26	3.51 ± 0.27	4.15 ± 0.13	4.20 ± 0.13
Difference, wrapped	4.06 ± 0.37	3.87 ± 0.13	4.32 ± 0.13	4.35 ± 0.10
Ratio (unwrpd./wrpd.)	0.66 ± 0.09	0.91 ± 0.08	0.96 ± 0.04	0.97 ± 0.04
95% confidence limit on ratio	±0.08	±0.07	±0.04	±0.03

Note: This test was performed in the Washington, DC, area during the summer, when ambient temperatures of as much as 95°F occur frequently. An ambient temperature of 95°F was shown to produce temperatures up to 115°F (46°C) inside the dosimeters wrapped in aluminum foil, and temperatures up to 140°F (60°C) in dosimeters without foil wrap. Therefore, the fading of the lithium-borate elements could have been due in part to the high temperatures--although the fact that element 1 faded considerably more than element 2 speaks for the effect being mainly due to light.

5.7 Moisture Dependence (ANSI N545-1975, Section 4.3.7)

Performance specifications

The ratio of the response of dosimeters stored for a period equal to the field cycle in plastic bags containing water to that of dosimeters stored in dry plastic bags shall not be smaller than 0.90 or larger than 1.10.

Procedure

A batch of 20 unexposed dosimeters was used for this test, with 10 dosimeters placed in a dry zip-lock plastic bag and 10 dosimeters supported about two to three inches above the water level in another zip-lock plastic bag. The bags were locked and placed in an area of the laboratory in which the exposure rate was monitored periodically and was expected to remain constant. All dosimeters were read out at the end of three months. The averages and standard deviations from the averages were obtained for all readings. The ratios formed of the averages of the readings for the "wet" and "dry" conditions, along with their standard deviations and the 95-percent confidence limits on the ratios, were computed as in 5.3.

Results

The detailed results are shown in Table A-14, which gives, for each type of dosimeter element, the averages of the readings and the associated standard deviations, the "wet"-to-"dry" ratios and associated standard deviations, and the 95-percent confidence limits on the ratios. Both lithium-borate elements stored under "wet" conditions were discolored, and their response was practically obliterated. Thus, when dosimeter response is determined with the lithium-borate elements, the dosimeters fail. They pass when response is determined with the calcium-sulfate elements. The pass-fail information for this test is included in Table A-8.

Table A-14. Moisture Dependence of TLD Response

	RESPONSE			
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm element	
	1	2	3	4
Dry Controls	0.64 ± 0.06	0.48 ± 0.04	0.57 ± 0.07	0.59 ± 0.02
Wet Badges	0.02 ± 0.02	0.005 ± 0.009	0.57 ± 0.06	0.61 ± 0.07
Ratio (wet/dry)	0.03 ± 0.04	0.01 ± 0.02	1.00 ± 0.15	1.04 ± 0.12
95% confidence limit on ratio	±0.02	±0.01	±0.09	±0.07

5.8 Self-irradiation (ANSI N545-1975, Section 4.3.8)

Performance specifications

For TLDs deployed during a period equal to the field cycle in an area in which the exposure rate is <10 μR/h, the exposure inferred from the TLD response shall not differ from the known exposure by more than an exposure equal to that resulting from a rate of 10 μR/h during the field cycle.

Procedure

Around 40 individually calibrated dosimeters were deployed for three months where a continuous environmental radiation monitor indicated an exposure rate of ~3.6 μR/h (or a total three-month exposure of 7.74 mR). At the end of the three-month deployment period, the dosimeters were read out and the individually corrected readings were interpreted in terms of exposure.

Results

Table A-15 shows the average exposure interpretation of the natural background exposure for all four dosimeter elements, and the difference between this exposure interpretation and the exposure calculated from the measured rate. The differences, in all instances, are seen to be well below the 21.6-mR exposure resulting from three months of deployment in a 10-μR/h field. Thus, the dosimeters passed the test on a confidence level approaching 100 percent.

Table A-15. Self-irradiation of TLDs

Dosimeter Element	Avg. Exposure Interpretation, mR (± stand. dev.)	Difference Between Avg. Exp. Interpret. and 7.74-mR Exposure Actually Received (± stand. dev.)
$Li_2B_4O_7$:Cu #1	9.6 ± 1.4	1.9 ± 1.4
#2	6.9 ± 1.1	-0.8 ± 1.1
$CaSO_4$:Tm #3	11.7 ± 0.7	3.9 ± 0.7
#4	11.7 ± 0.6	3.9 ± 0.6

6. Tests Going Beyond ANSI N545-1975

6.1 Directional Dependence, Discrete Angles of Incidence

Procedure

The experiment was performed similarly to the one described in 5.5, except that up to eight discrete angles of incidence were used.

(a) Results for bare dosimeters with low-scatter support

Figures A-6 through A-20 cover the results obtained in the low-scatter support geometry for rotation about the long ("major") and short ("minor") axes of the dosimeter (see sketch in table A-11), for seven radiation qualities, and for continuous rotation about the chosen axes (data from tables A-11 and A-12) as well as for discrete angles of radiation incidence. While the performance specifications, in accordance with the standard, are given only in terms of the response averaged over all directions, an inspection of the response for discrete angles of incidence aids in the understanding of the averaged results. Here are some of the striking features revealed in the figures:

- There is a pronounced over-response at low energies of the calcium-sulfate elements for lateral radiation incidence, for which the elements are not shielded by the lead filters. This shortcoming could be easily remedied (see recommendation to 5.5).
- Dosimeter response determined with lithium-borate element 1 shows the least dependence on direction of radiation incidence.

- There is an under-response of the lithium-borate elements for lateral radiation incidence, which probably could be remedied only by a redesign of the dosimeters. (Note, e.g., that the pronounced under-response at 270° for rotation about the minor axis is probably the result of the lead-filtered calcium sulfate elements shielding the lithium-borate elements.)
- As expected, some of the extreme features for certain angles of radiation incidence are averaged out.
- In environmental dosimetry applications, the major uncertainty in the exposure interpretation from the response of the lithium-borate elements probably is not due to angular dependence but to poor reproducibility of response, particularly at low irradiation levels. This is shown in Figure A-13, which gives the results for the angular dependence of the response of these elements at levels corresponding to a three-month irradiation at 10 μR/h.

(b) Results for field support geometries involving a utility pole

Table A-16 shows that, as expected, the main feature of the results as compared with the results for the dosimeters supported in a low-scatter geometry is the reduction of the response in the direction of radiation incidence in which the pole shields the dosimeter from the radiation beam. This effect decreases with increasing distance of the dosimeters from the pole and with increasing photon energy. In the worst case (effective photon energy of 38 keV), the response of the lithium-borate elements in the direction in which the pole is completely shielding the dosimeters is only ~8 percent of that for perpendicular radiation incidence, regardless of which support geometry is used; for the calcium sulfate elements, the corresponding responses are ~15, ~18, and ~40 percent, respectively, for the dosimeters attached directly to the pole, the dosimeters in the cage, and the dosimeters taped to the spoke. At this low energy, the difference between the response for the various support geometries is much more pronounced for directions of partial shielding (say, 45 degrees off the direction of complete shielding):

- For the case of the dosimeters placed directly against the pole, dosimeter response determined with lithium-borate is seen to be still reduced to between 10 and 15 percent relative to that at perpendicular radiation incidence.
- There is seen to be only a slight improvement for the cage support.
- Yet, for the dosimeters on the spoke, there is essentially no effect of the pole on dosimeter response 45 degrees off the direction of complete shielding.

At the low energies. the spoke geometry also assists in removing the orders-of-magnitude over-response of the calcium sulfate elements for the lateral irradiation direction, at least when the dosimeters are oriented so as to have the pole shield them laterally. However, this result could be achieved also (and even more effectively) by incorporating a lateral lead shield into the dosimeters.

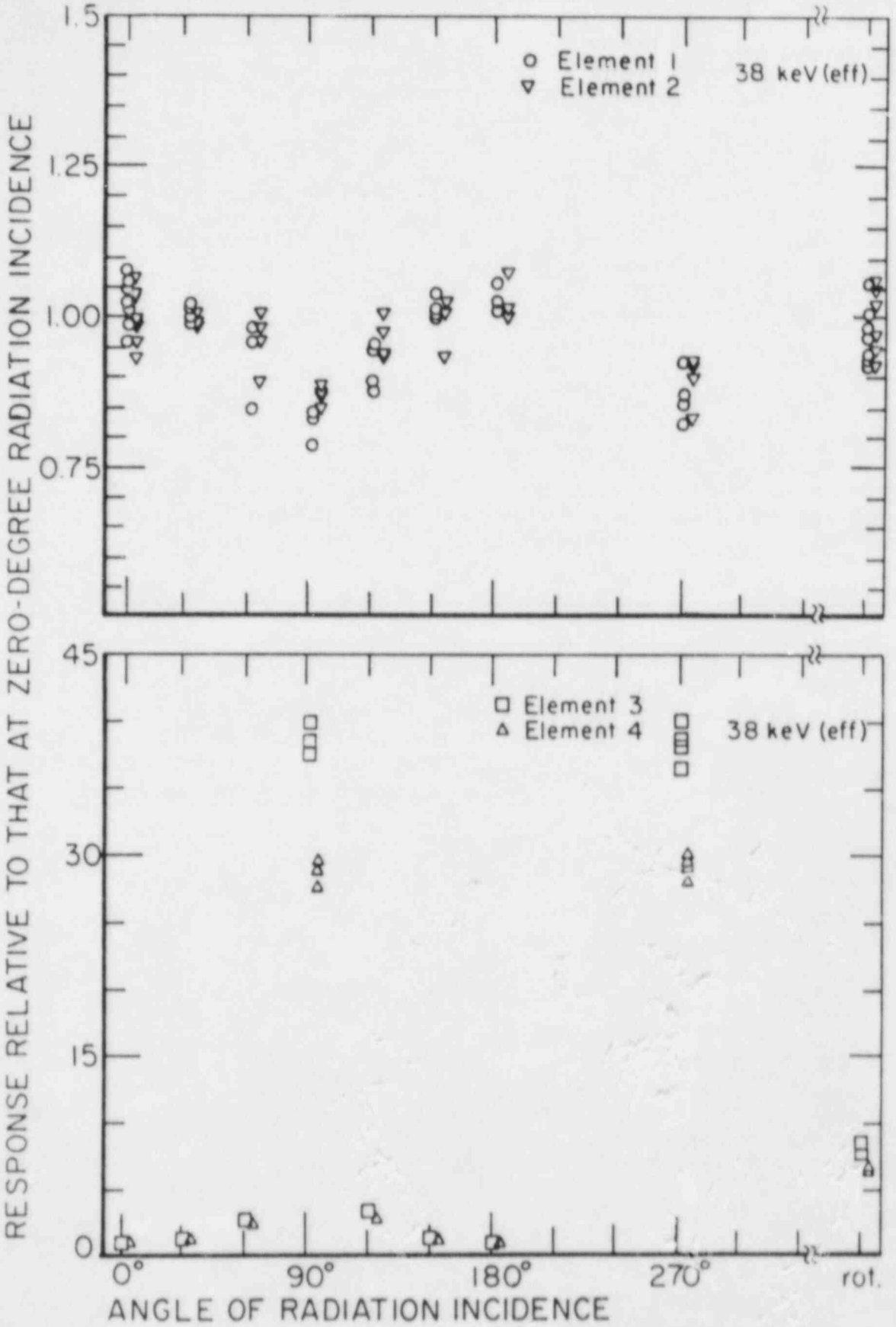


Figure A-6 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 38 keV

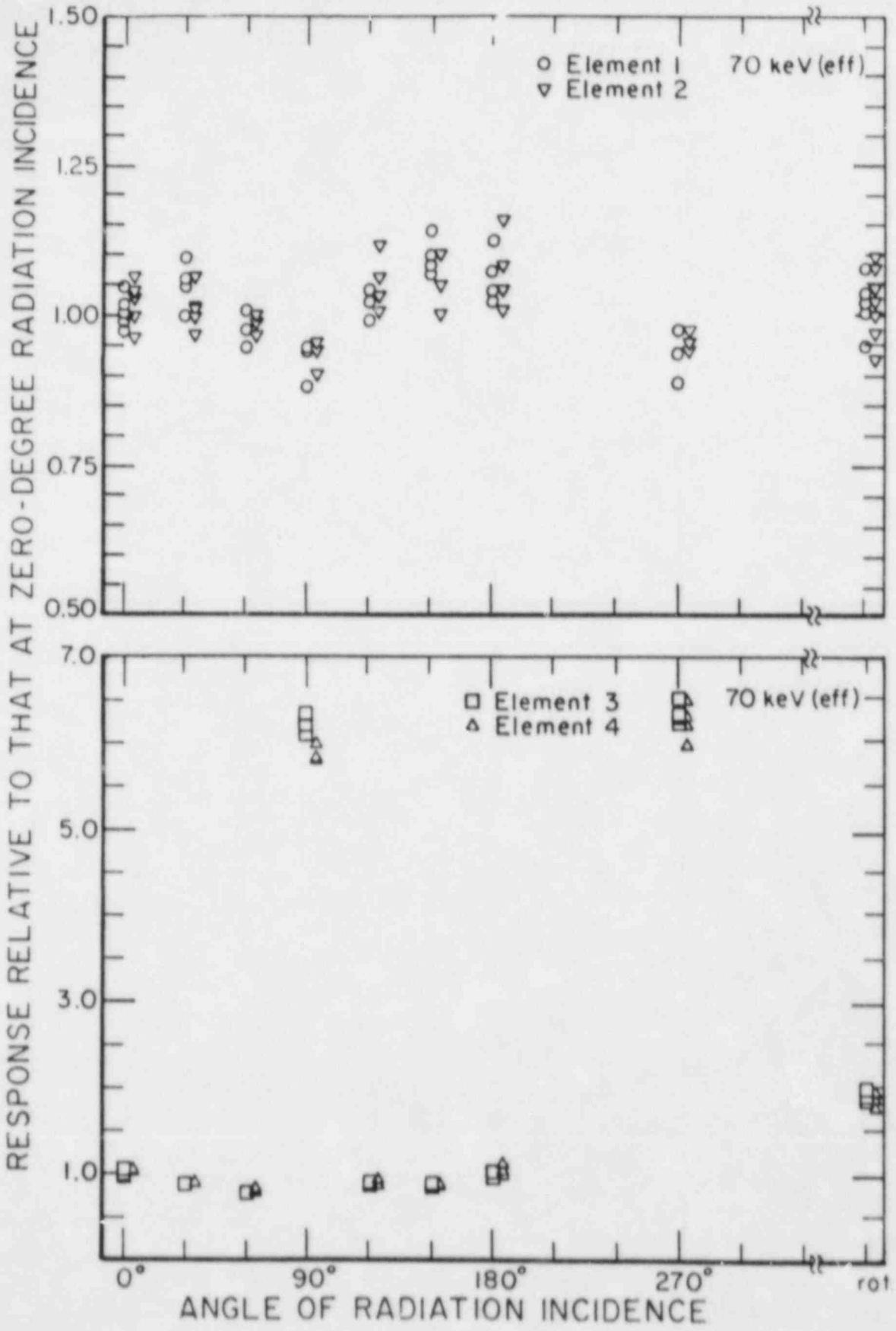


Figure A-7 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 70 keV

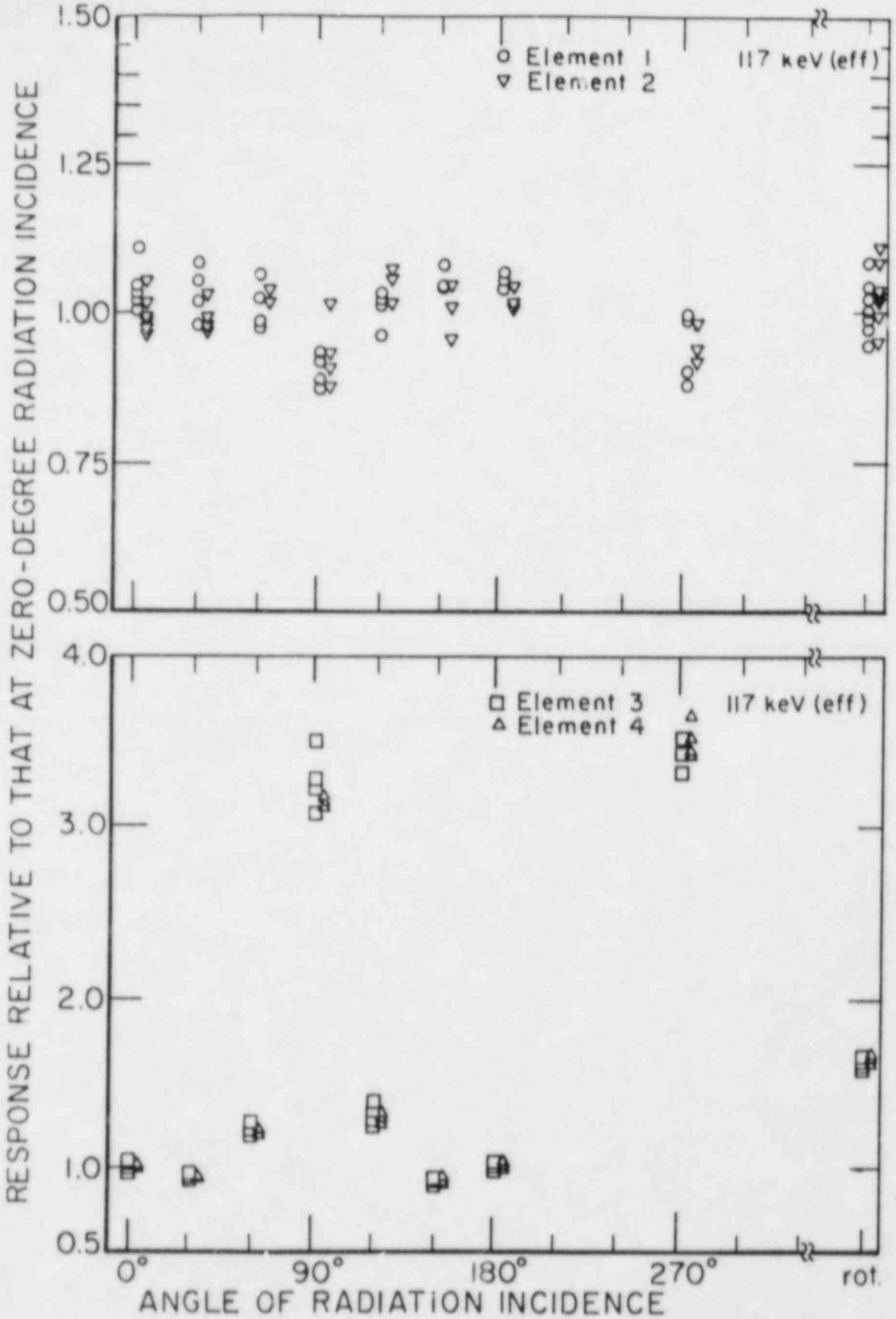


Figure A-8 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis, Irradiation Level: ~120 mR; Effective Radiation Energy: 117 keV

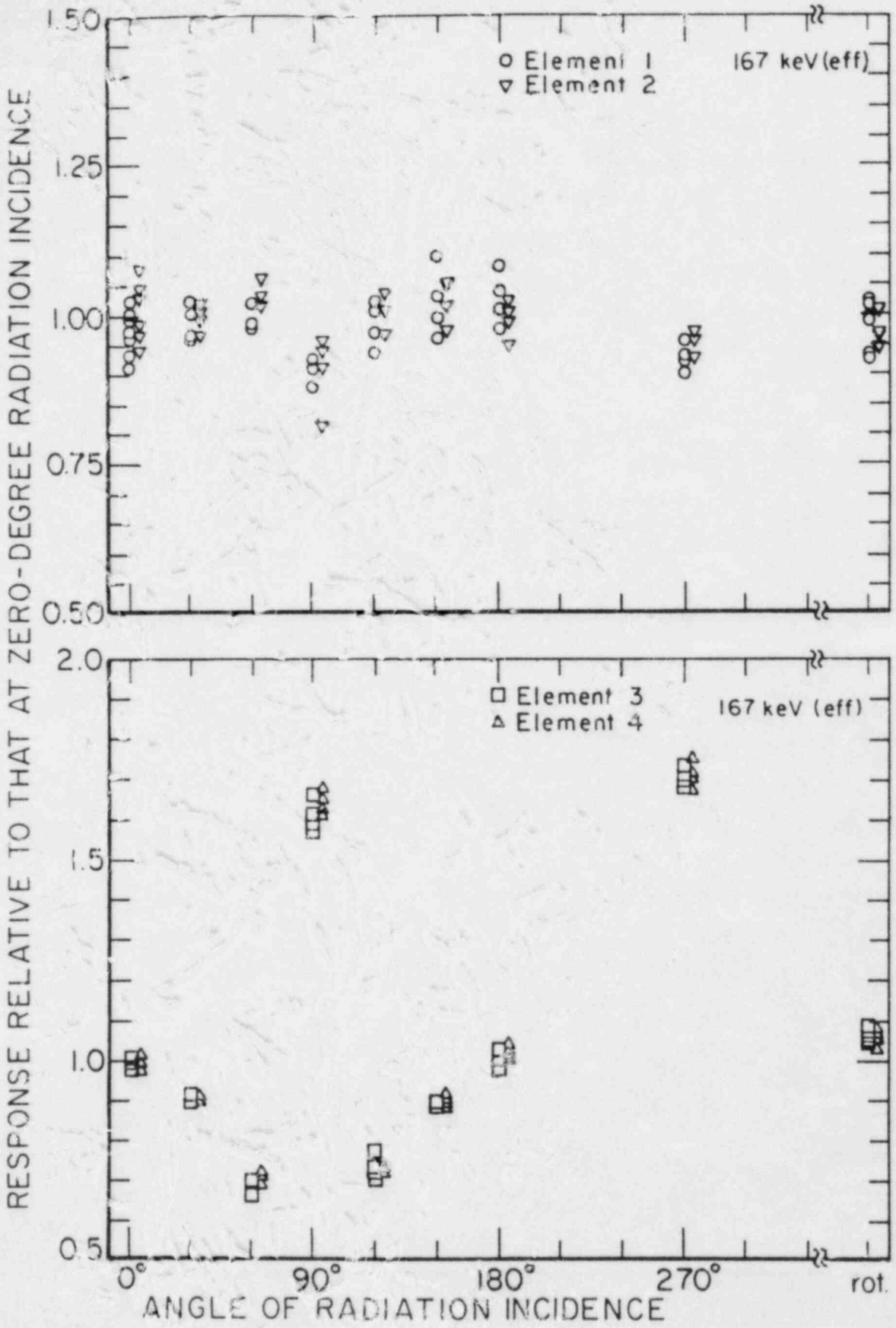


Figure A-9 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 167 keV

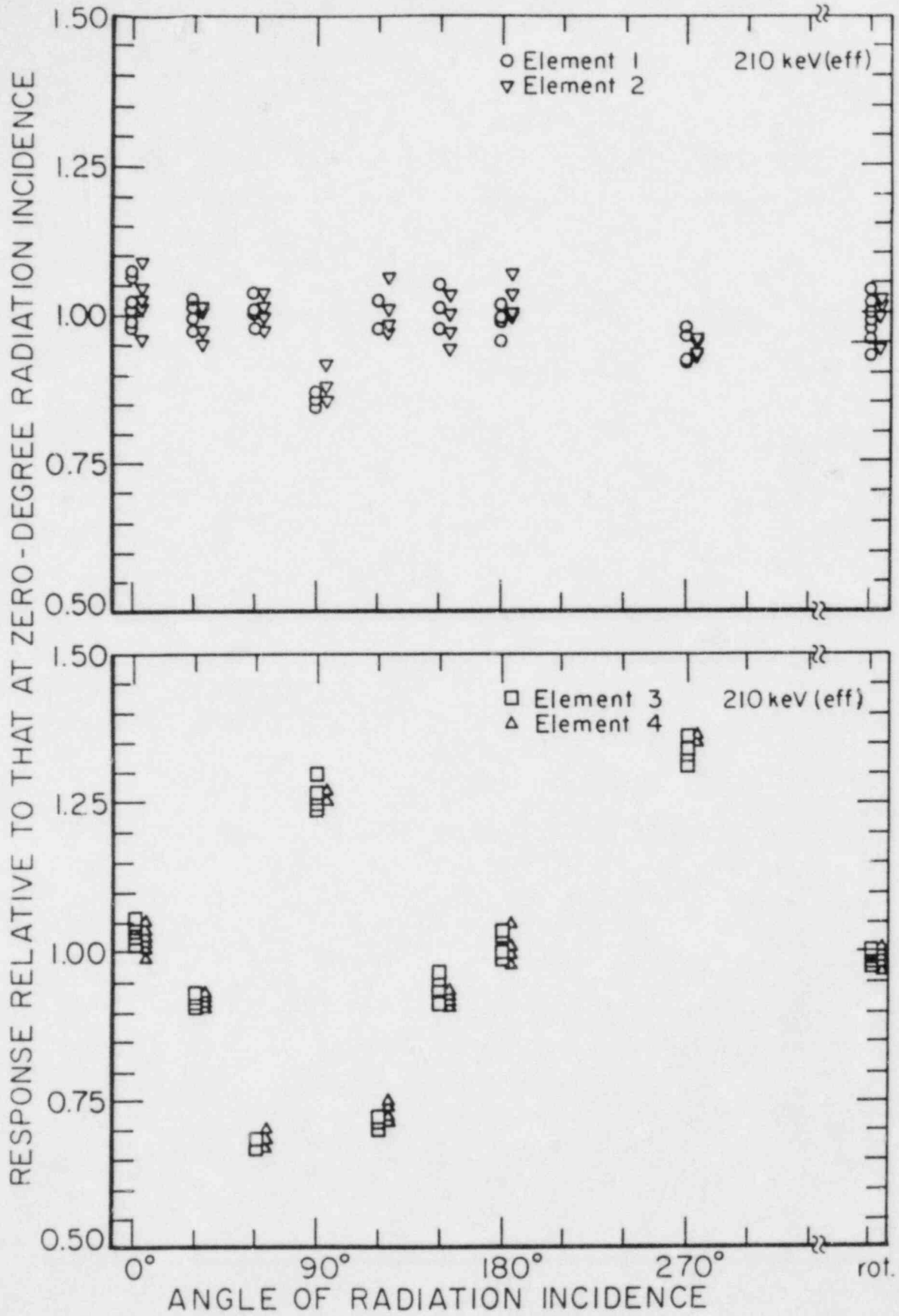


Figure A-10 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 210 keV

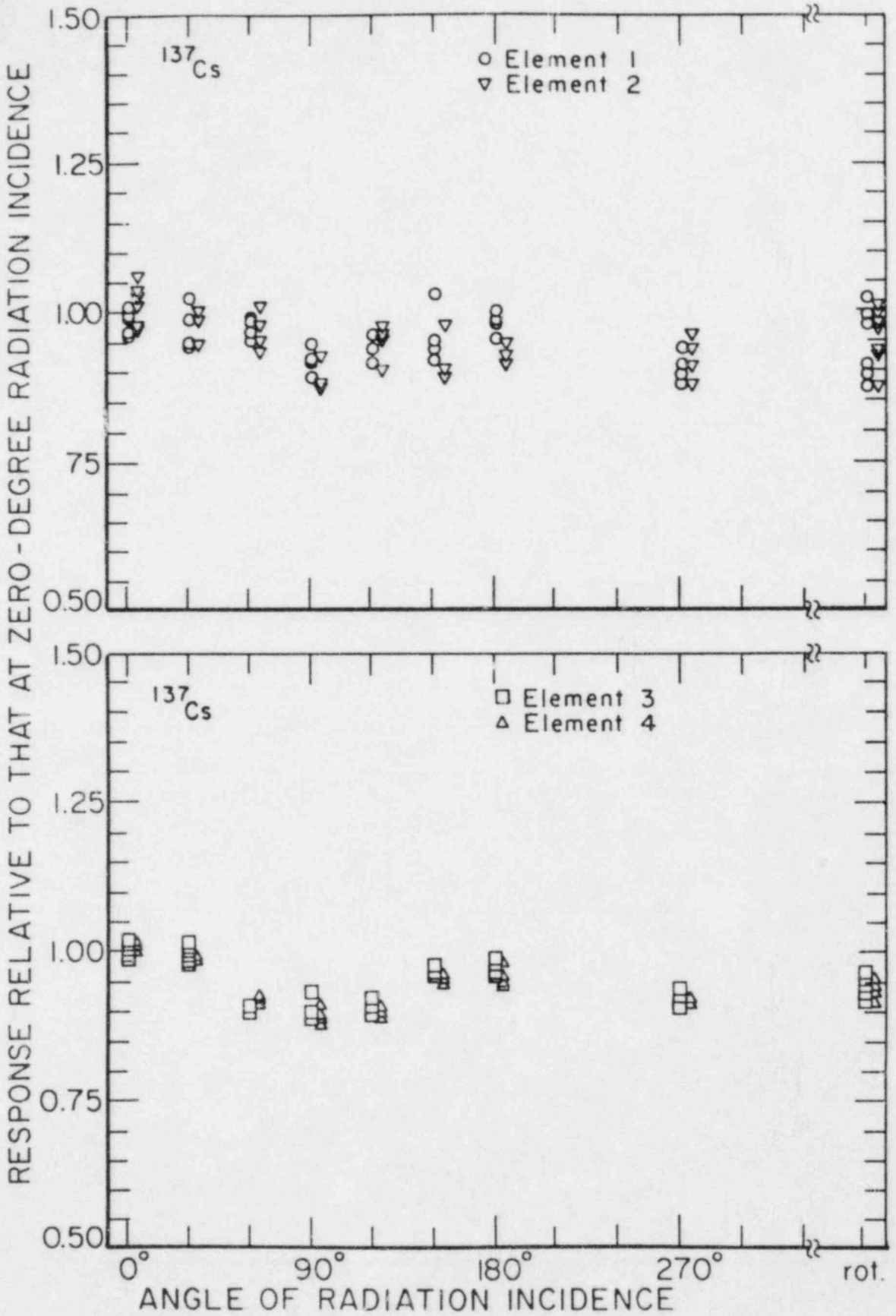


Figure A-11 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 662 keV

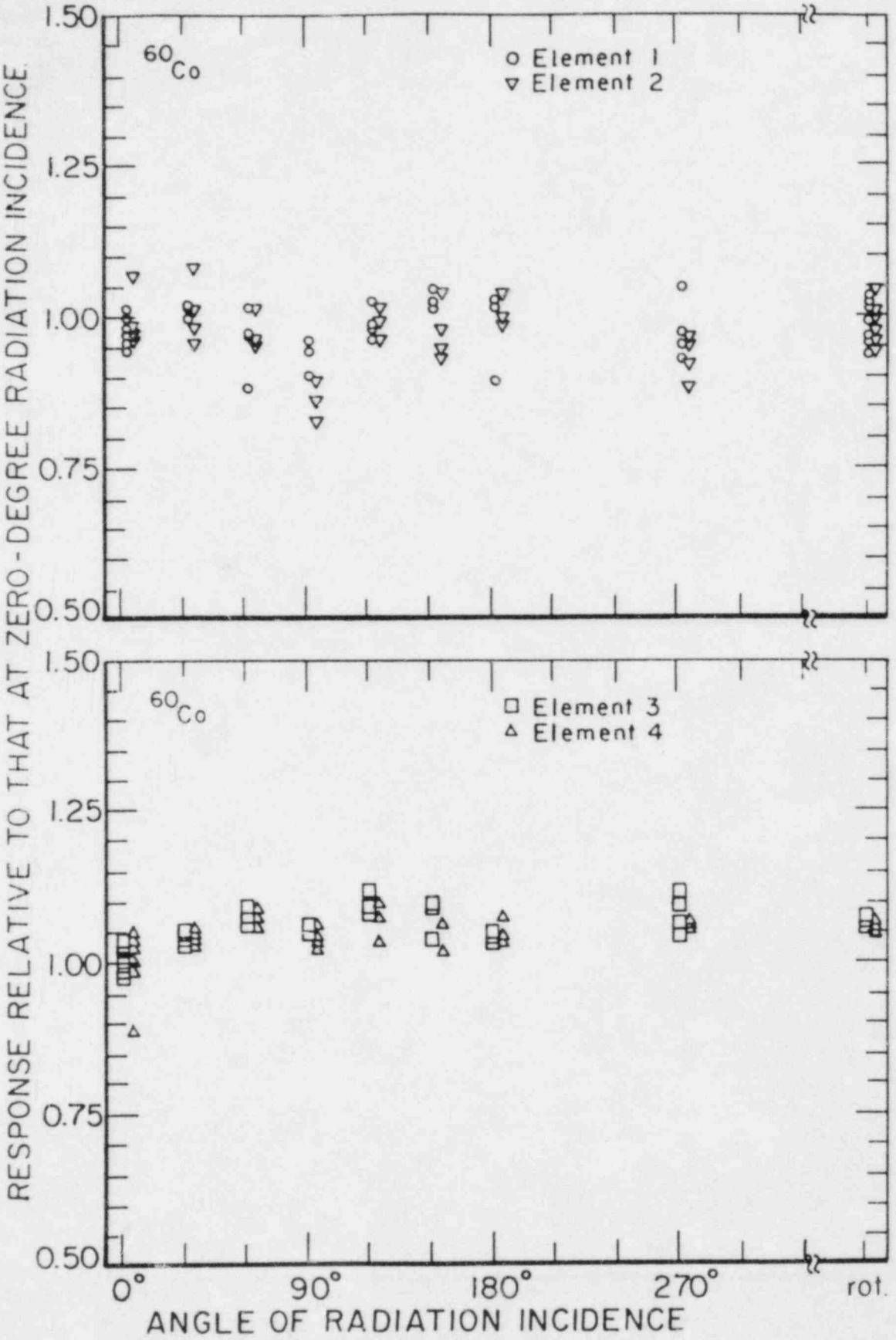


Figure A-12 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 1.25 keV

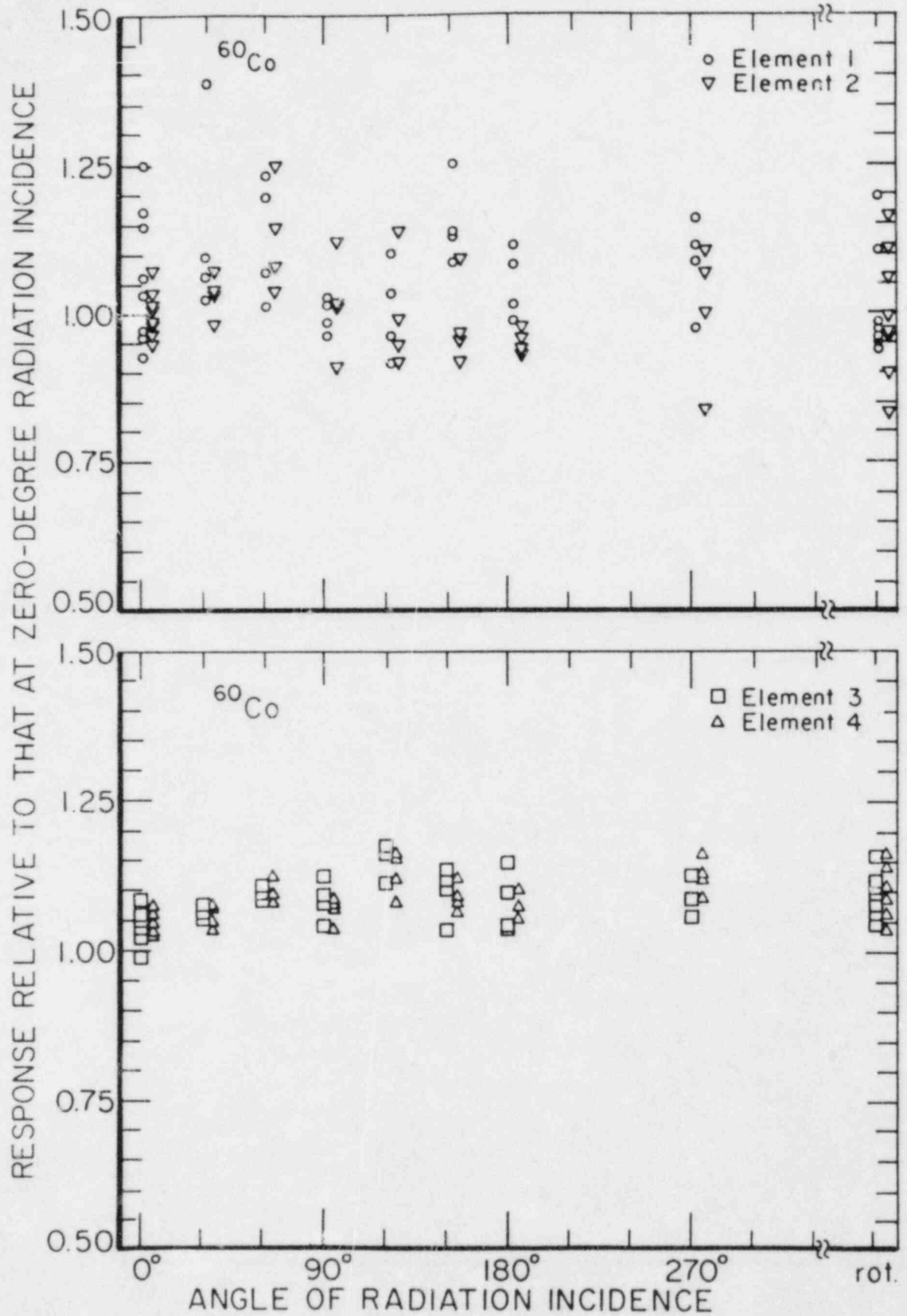


Figure A-13 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Long ("Major") Dosimeter Axis. Irradiation Level: ~2.16 mR; Effective Radiation Energy: 1.25 keV

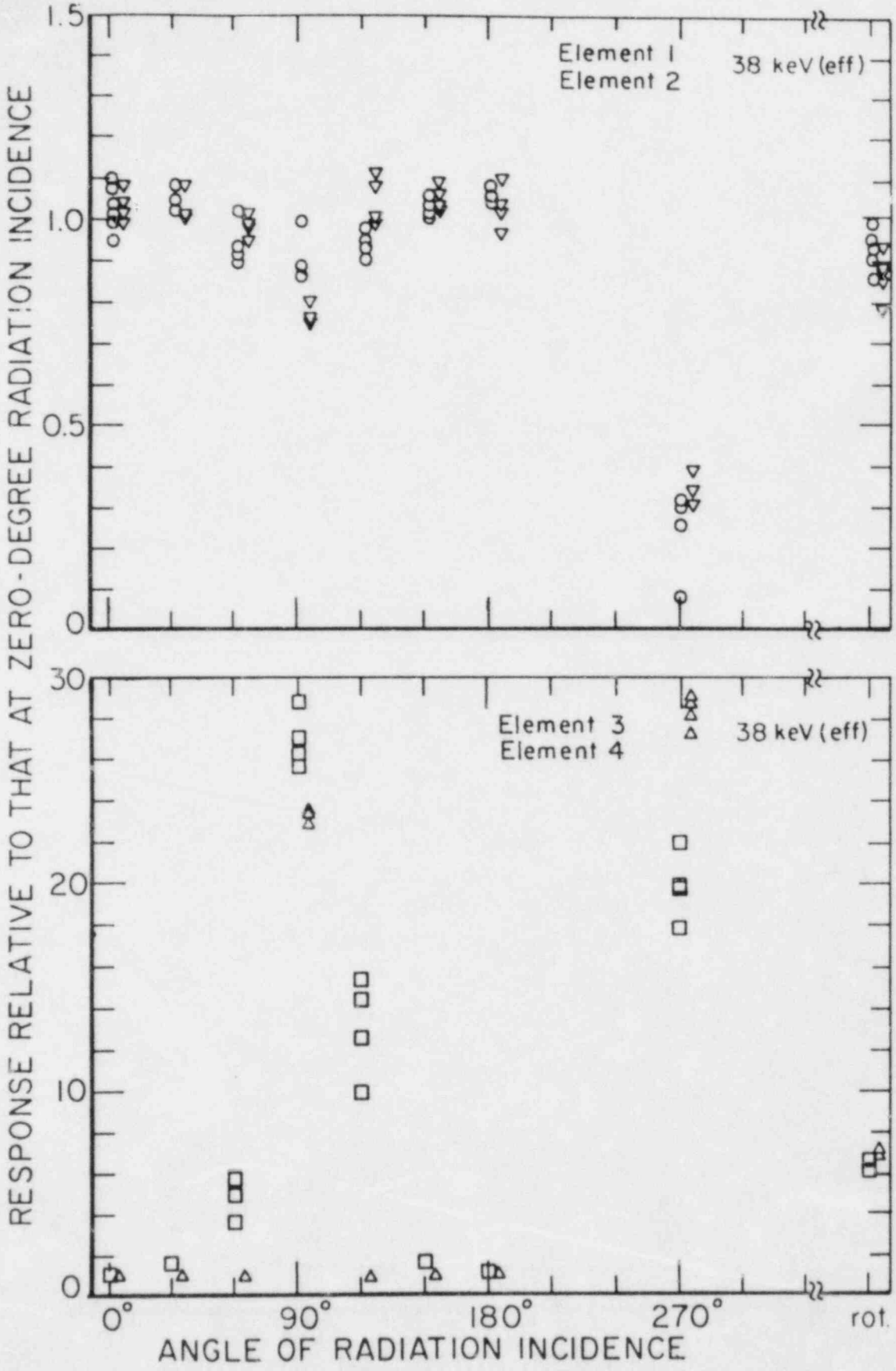


Figure A-14 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Short ("Minor") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 38 keV

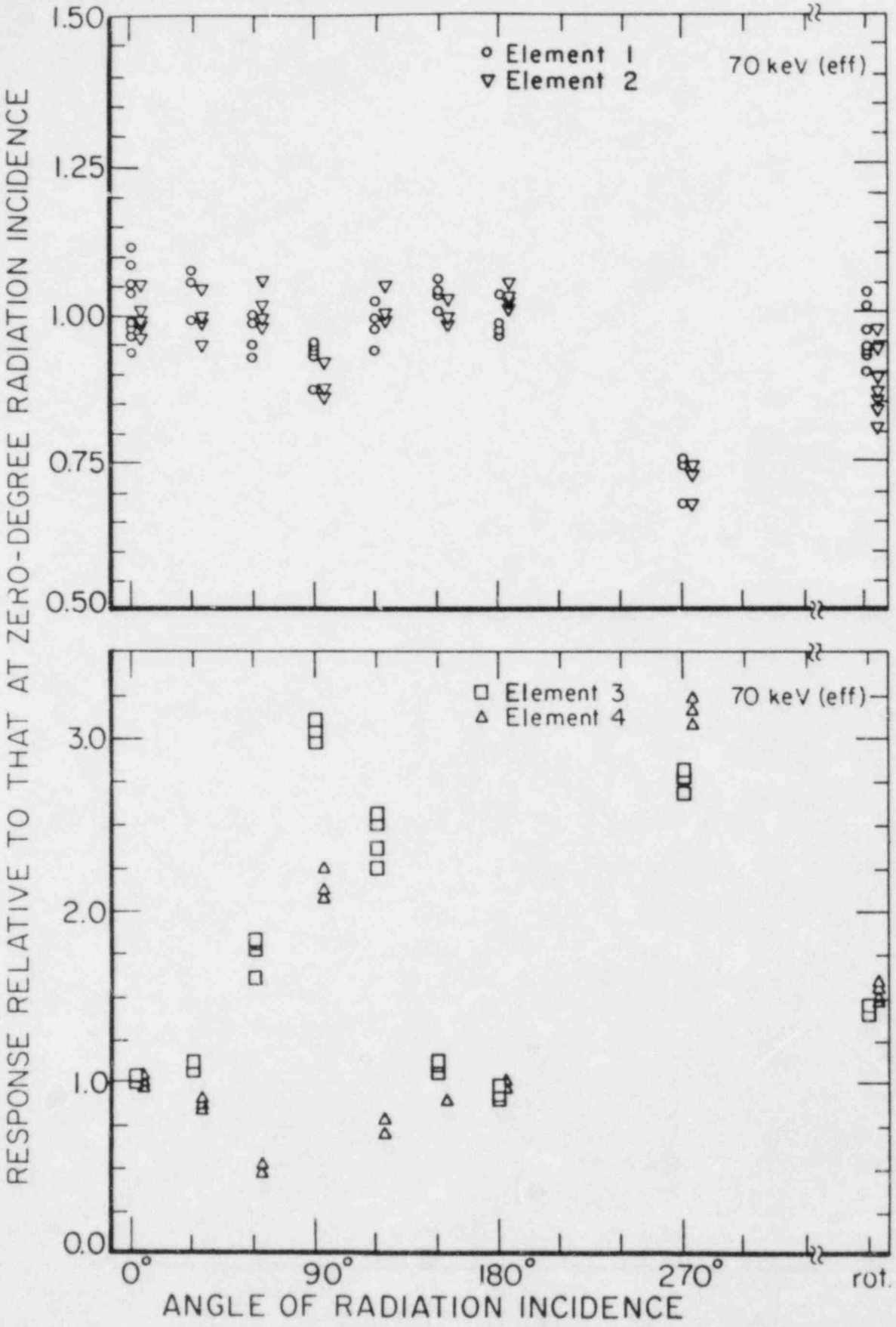


Figure A-15 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Short ("Minor") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 70 keV

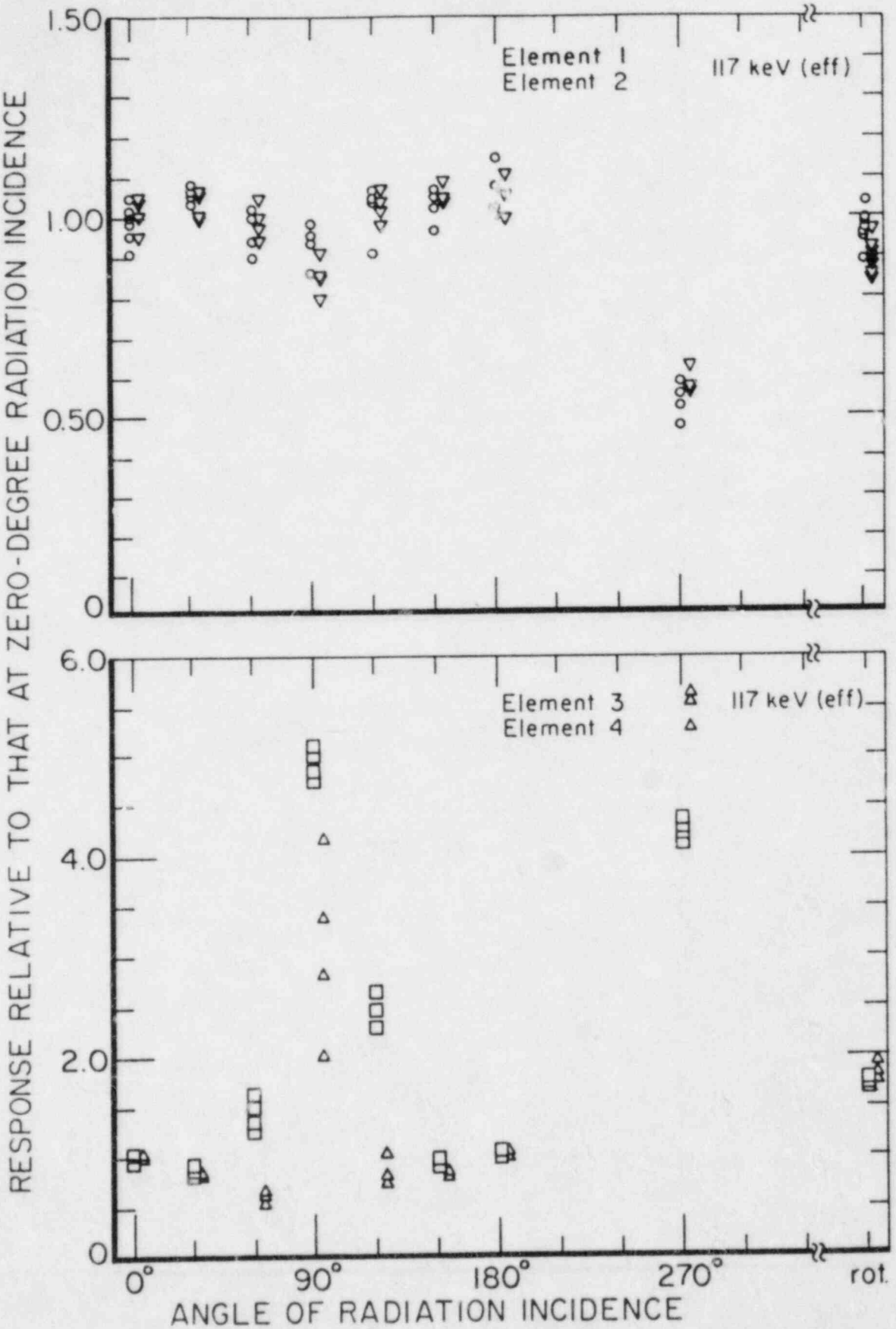


Figure A-16 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Short ("Minor") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 117 keV

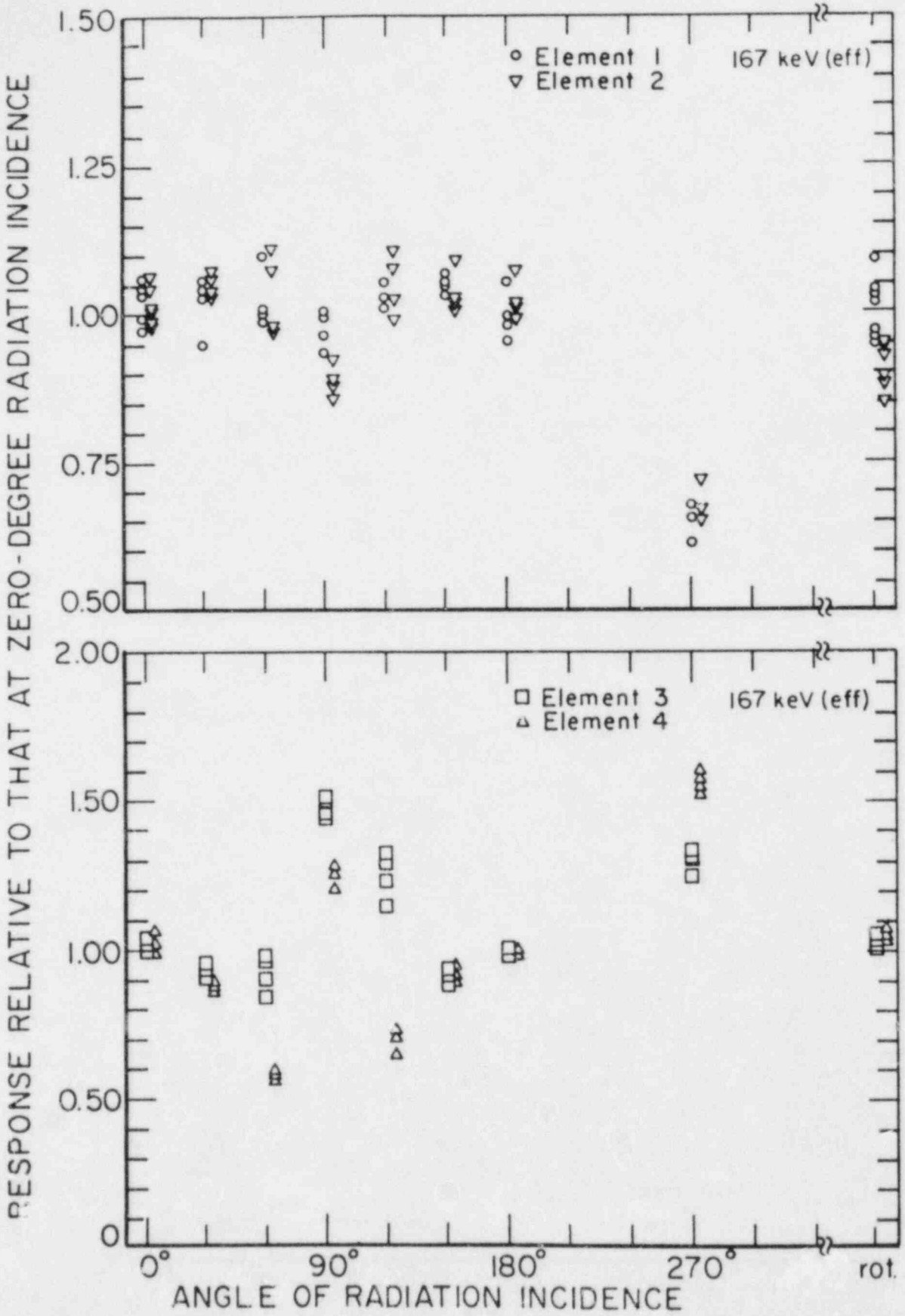


Figure A-17 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Short ("Minor") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 167 keV

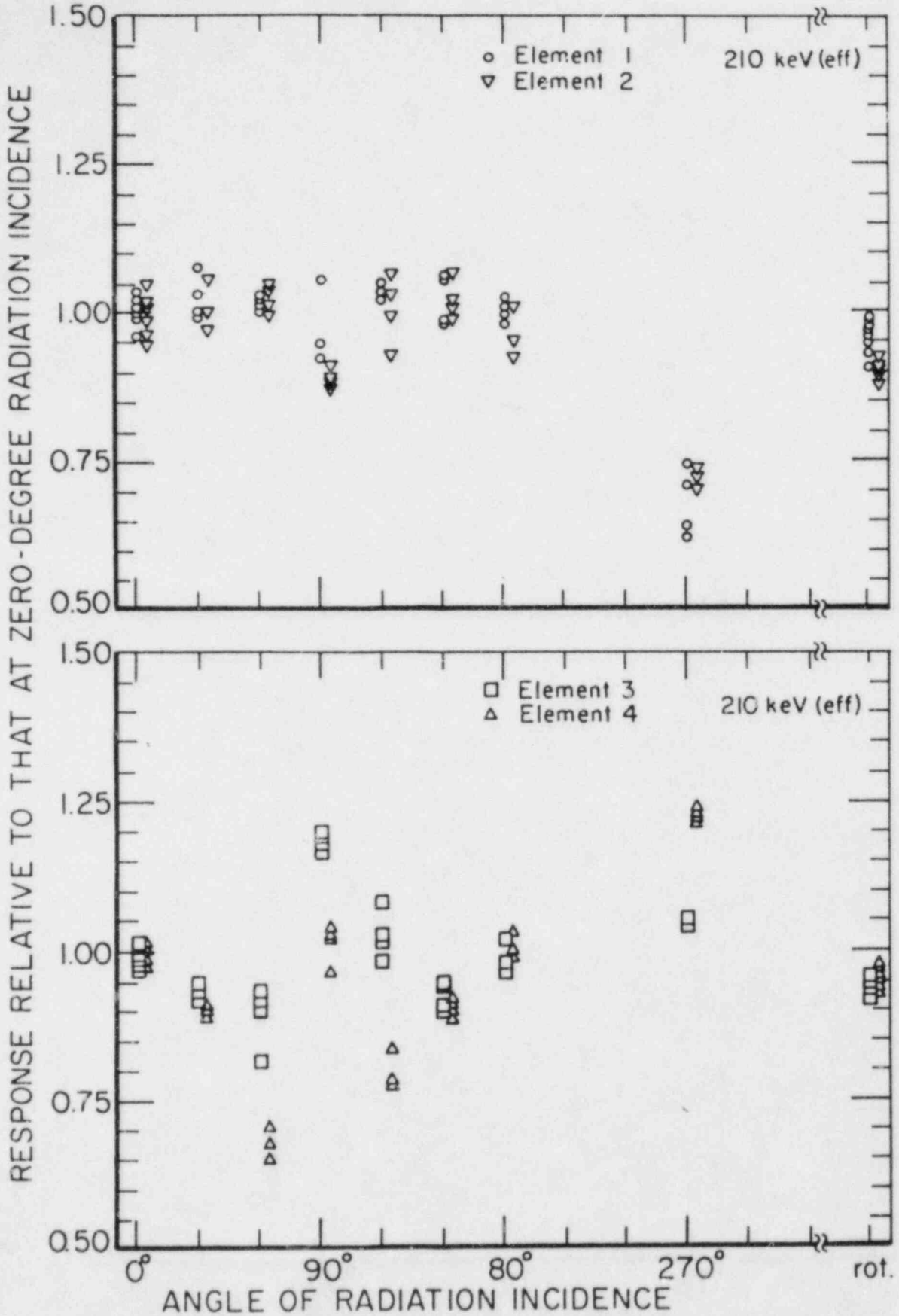


Figure A-18 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Short ("Minor") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 210 keV

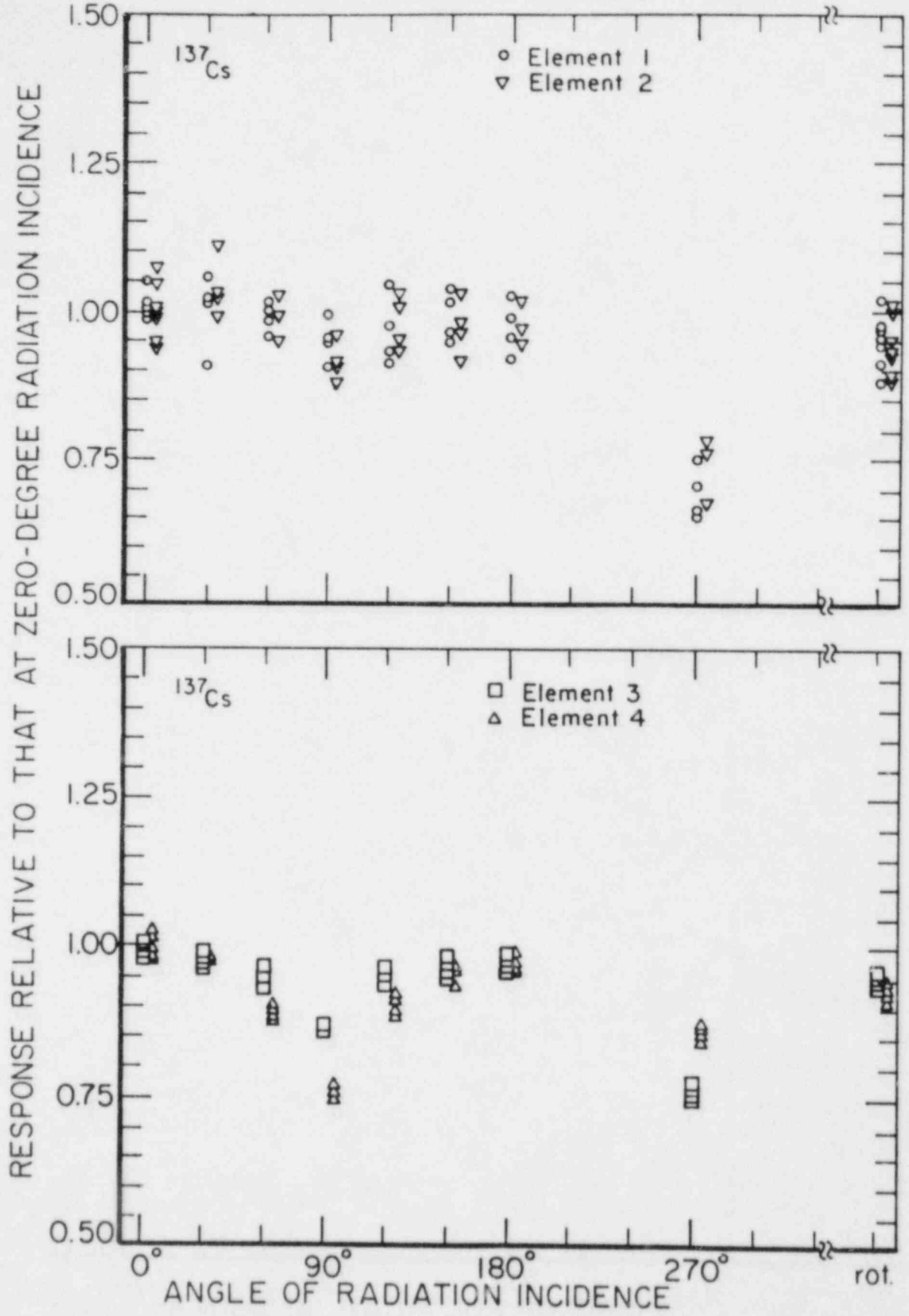


Figure A-19 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Short ("Minor") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 662 keV

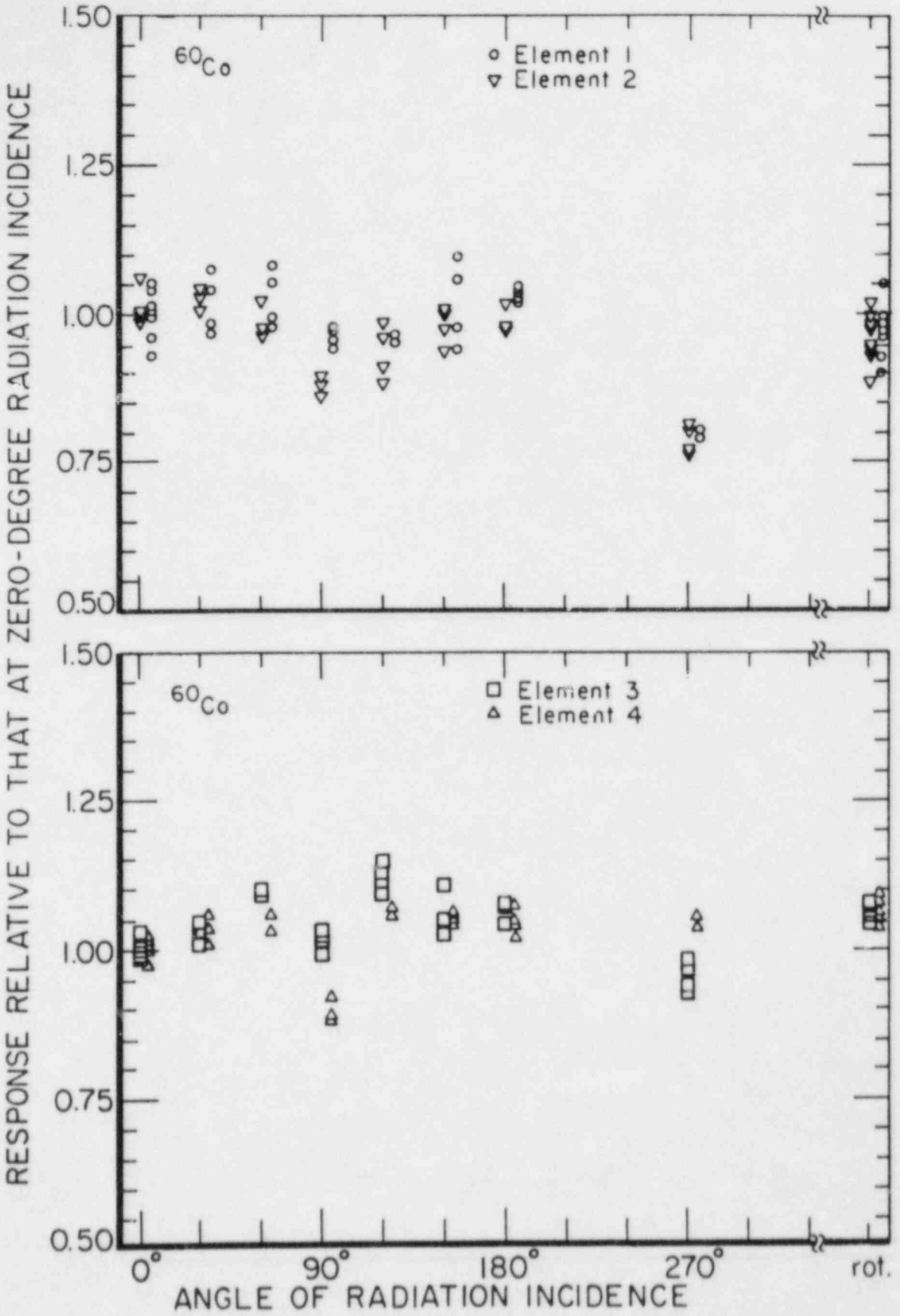
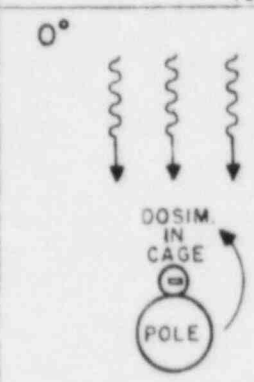
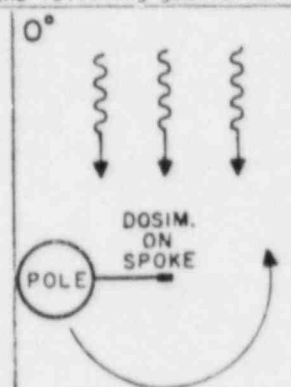
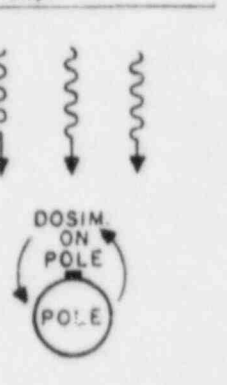


Figure A-20 Angular Dependence of Response of Dosimeters in Low-Scatter Geometry, for Rotation about Short ("Minor") Dosimeter Axis. Irradiation Level: ~120 mR; Effective Radiation Energy: 1.25 keV

Table A-16. Dependence of TLD Response on Direction of Radiation Incidence, with Dosimeters Hung on Wooden Pole in Three Different Ways

Effective photon energy and angle of radiation incidence	Response relative to that for perpendicular radiation incidence for the following geometries (plan view):											
												
	in cage for element				taped to spoke for element				attached directly to pole for element			
	1	2	3	4	1	2	3	4	1	2	3	4
38 keV												
45°	0.94	0.97	1.59	1.52	1.05	1.03	1.53	1.55	0.94	0.91	1.14	1.10
90°	0.69	0.77	12.3	12.1	0.74	0.74	8.10	7.42	0.65	0.67	3.47	3.82
135°	0.24	0.24	0.50	0.50	1.02	1.00	1.76	1.66	0.25	0.25	0.59	0.57
180°	0.07*	0.08*	0.17*	0.20*	1.04	1.02	1.06	1.06	0.08*	0.07*	0.13*	0.16*
225°	0.21	0.20	0.41	0.41	0.99	1.00	1.38	1.30	0.10	0.10	0.18	0.19
270°	0.81	0.83	17.6	14.6	0.08*	0.08*	0.39*	0.44*	0.82	0.88	13.4	11.6
315°	0.93	0.96	1.58	1.48	0.98	1.01	1.57	1.50	0.92	0.97	1.56	1.48
117 keV												
45°	0.96	0.99	0.96	0.97	0.99	0.99	0.98	0.97	0.97	1.00	0.93	0.88
90°	0.87	0.89	2.58	2.43	0.81	0.83	2.74	2.66	0.85	0.84	2.24	2.18
135°	0.50	0.53	0.55	0.59	0.96	0.97	1.02	1.02	0.35	0.33	0.43	0.47
180°	0.20*	0.19*	0.26*	0.31*	1.01	0.95	1.00	1.02	0.21*	0.21*	0.29*	0.33*
225°	0.46	0.45	0.49	0.52	0.99	1.05	1.00	0.98	0.32	0.31	0.41	0.43
270°	0.92	0.95	2.83	2.58	0.16*	0.16*	0.52*	0.61*	0.90	0.92	2.73	2.51
315°	1.01	1.03	1.01	0.97	1.00	1.03	1.14	1.08	0.97	0.97	1.05	1.00
210 keV												
45°	1.00	1.00	0.87	0.88	1.03	1.01	0.90	0.89	0.99	0.97	0.85	0.86
90°	0.91	0.94	1.31	1.30	0.90	0.90	1.27	1.28	0.92	0.94	1.28	1.28
135°	0.53	0.57	0.49	0.50	1.05	1.01	0.74	0.82	0.41	0.41	0.37	0.38
180°	0.24*	0.24*	0.25*	0.26*	1.40	1.38	1.46	1.47	0.27*	0.25*	0.26*	0.28*
225°	0.57	0.57	0.52	0.53	1.05	1.05	0.93	0.93	0.40	0.41	0.37	0.38
270°	0.98	1.01	1.45	1.44	0.20*	0.20*	0.32*	0.35*	1.00	1.00	1.38	1.39
315°	1.05	1.04	0.87	0.87	1.00	1.03	0.86	0.87	1.02	1.01	0.86	0.86
1250 keV												
45°	0.92	0.99	1.04	1.04	0.95	1.02	1.03	1.05	1.02	0.94	1.03	1.05
90°	0.94	0.94	1.03	1.03	0.92	0.92	1.04	1.03	1.02	0.98	1.08	1.09
135°	0.88	0.95	0.88	0.86	1.00	0.97	1.03	1.03	0.81	0.73	0.72	0.72
180°	0.59*	0.55*	0.49*	0.50*	0.99	1.01	0.95	0.97	0.56*	0.58*	0.51*	0.51*
225°	0.85	0.82	0.77	0.80	1.02	1.05	1.02	1.05	0.76	0.66	0.64	0.64
270°	1.14	0.99	1.05	1.05	0.55*	0.47*	0.46*	0.47*	1.23	1.10	1.08	1.10
315°	1.08	1.01	1.06	1.05	1.03	1.02	1.06	1.06	0.98	0.97	1.05	1.02

*Dosimeters completely shielded from source by pole.

6.2 The Salt-Spray Test

Performance specifications

For dosimeters deployed at a reactor site near the seashore, the quotient of the response obtained for the field cycle to twice that obtained for one-half of the field cycle shall not be less than 0.90.

Procedure

In mid-July 1982, 10 fully characterized dosimeters were taken to the NRC Region-1 laboratory for deployment at a reactor site in New Jersey. Five of the badges were deployed for roughly one-half of one field cycle and returned for readout in September; the other five remained deployed for one full field cycle and were then returned for readout in late October. After readout, the average response, corrected for post-readout residuals, was calculated for each of the four elements of the five dosimeters that had been deployed for the same length of time, and the ratio was determined of the average responses for the full field cycle (108 days) and of 108/63 times the average responses for the partial field cycle (63 days).

Results

Table A-17 shows the results of this evaluation, giving average readings, standard deviations, and 95-percent confidence limits on the desired ratios. The dosimeters are seen to pass easily when the calcium-sulfate elements are used for the evaluation, pass when lithium-borate element 2 is used, but fail for element 1.

Table A-17. Results of Salt-Spray Test

	RESPONSE			
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm element	
	1	2	3	4
Readout after:				
partial cycle	0.58 ± 0.06	0.40 ± 0.04	0.49 ± 0.02	0.49 ± 0.01
whole cycle	1.09 ± 0.13	0.78 ± 0.04	0.87 ± 0.02	0.87 ± 0.01
Ratio[1]	1.09 ± 0.18	1.15 ± 0.12	1.04 ± 0.05	1.04 ± 0.03
95% confidence limit on ratio	±0.22	±0.15	±0.06	±0.04

[1] Response for whole cycle divided by 108/63 times response for partial cycle (see text).

6.3 Dosimeter Drop Tests

A group of 48 individually characterized dosimeters was divided into four subgroups of 12 dosimeters each. The dosimeters in two of the subgroups were left unirradiated and the others were given an exposure of ~20 mR. Subsequently, the dosimeters of one of the irradiated and one of the unirradiated subgroups (a total of 24 dosimeters) were dropped individually from a height of 10 feet onto concrete. No damage was observed on any of the dosimeters. They were read out in the usual manner and re-characterized, along with the two groups of dosimeters that had not been dropped (controls). The average responses of the dropped dosimeters and of the controls are shown in Table A-18, along with the associated standard deviations. No effect on dosimeter response is evident.

Table A-18. Comparison, Response of Dropped Dosimeters and of Controls

Condition	RESPONSE			
	$Li_2B_4O_7$:Cu element		$CaSO_4$:Tm element	
	1	2	3	4
Dropped, irradiated	0.97 ± 0.06	0.99 ± 0.08	0.99 ± 0.02	0.99 ± 0.02
Control, irradiated	1.02 ± 0.09	0.99 ± 0.07	1.00 ± 0.03	0.99 ± 0.02
Dropped, unirradiated	0.01 ± 0.04	0.03 ± 0.04	0.02 ± 0.01	0.02 ± 0.01
Control, unirradiated	0.02 ± 0.03	0.02 ± 0.02	0.02 ± 0.01	0.02 ± 0.01

6.4 Response to Beta Particles

Procedure

A study was performed of the response of the dosimeters to the three beta-particle sources described in Table A-19. Six of a set of individually characterized dosimeters were irradiated one at a time on each source, two each at three levels of absorbed dose to water between 25 and 100 mrad. Absorbed dose delivered at the surface and at 7 mg/cm^2 was calculated from available source-calibration data. Other dosimeters of the same set were given Co-60 gamma-ray exposures. After correction for differences in individual dosimeter sensitivities, beta-particle dose delivered was evaluated in terms of absorbed dose to water and plotted against Co-60 gamma-ray response evaluated in terms of exposure. Over the range of irradiation levels covered, these plots were linear, the slopes representing the conversion factors to absorbed-dose interpretation from Co-60 gamma-ray exposure interpretation of a given dosimeter response to beta-particles.

Results

Table A-20 shows the values of the conversion factors with 95-percent confidence intervals for all four dosimeter elements and for the four beta-particle sources employed at the indicated source-to-dosimeter distances. Following is a discussion of the results shown in the table.

Table A-19. Amersham-Bucnler Beta-Particle Sources

(a) Physical Characteristics of Sources Supplied to NBS

Type of Source and Appr. Half Life	Radioactive Element	Source Encapsulation	Nominal Activity, MBq(mCi); date
$^{90}Sr/^{90}Y$ 28.5y	^{90}Sr carbonate pressed(1) into Ag foil	50 mg/cm^2 Ag +0.1 mm steel	1850(50); December 1982
$^{90}Sr/^{90}Y$ 28.5y	^{90}Sr carbonate pressed(1) into Ag foil	50 mg/cm^2 Ag +0.1 mm steel	74(2); December 1982
^{204}Tl 3.78y	^{204}Tl pressed(1) into Ag foil	20 mg/cm^2 Ag	18.5(0.5); December 1982
^{147}Pm 2.62y	^{147}Pm pressed(1) into Ag foil	5 mg/cm^2 Ag	518(14); December 1982

(b) Beta-Particle Ranges

Type of Source	Avg. and Max. Beta-Particle Energies (MeV)(3)	Range in air		Range in plastic	
		cm	mg/cm^2	cm	mg/cm^2
^{90}Sr(2)	$\bar{E}$ = 0.196	41	49		
	E_{max} = 0.546	187	225	0.17	204
^{90}Y	$\bar{E}$ = 0.935	375	452		
	E_{max} = 2.284	1037	1249	0.98	1170
^{204}Tl	$\bar{E}$ = 0.244	58	70		
	E_{max} = 0.763	291	351	0.27	320
^{147}Pm	$\bar{E}$ = 0.062	59	7.2		
	E_{max} = 0.225	51	61	0.047	56

(1) During the rolling stage.

(2) Essentially, none of the beta particles from ^{90}Sr penetrate the combined filtration of (1) the source encapsulation, (2) the 10 cm of air between source and beam-flattening filter, and (3) the beam-flattening filter.

(3) Average and maximum energies are for ideal point source.

Table A-20. Conversion Factors from Dosimeter Response in Terms of ^{60}Co Gamma-Ray Exposure to Response to Beta-Particles in Terms of Absorbed Dose to Water

(a) At the water surface

Type of Source	Distance (cm)	Conversion Factor			
		Element 1	Element 2	Element 3	Element 4
^{147}Pm	20	---	---	---	---
^{204}Tl	30	1.25 ± .07	---	---	---
$^{90}Sr/^{90}Y$ (50 mCi)	50	0.59 ± .05	1.14 ± .10	29 ± 2	29 ± 4
$^{90}Sr/^{90}Y$	30	0.58 ± .05	1.02 ± .07	31 ± 3	30 ± 3

(b) At a 7 mg/cm^2 depth in water

Type of Source	Distance (cm)	Conversion Factor			
		Element 1	Element 2	Element 3	Element 4
^{147}Pm	20	---	---	---	---
^{204}Tl	30	1.19 ± .06	---	---	---
$^{90}Sr/^{90}Y$ (50 mCi)	50	0.62 ± .05	1.19 ± .11	30 ± 2	31 ± 4
$^{90}Sr/^{90}Y$ (2mCi)	30	0.60 ± .06	1.06 ± .07	32 ± 3	32 ± 3

Response to $^{90}Sr/^{90}Y$ beta particles (E_{max} = 2.28 MeV for ^{90}Y; ^{90}Sr beta particles are essentially removed by source filtration). For lithium-borate element 2 under 300 mg/cm^2 of plastic, the interpretation of the response in terms of beta-particle dose is seen to differ from that in terms of ^{60}Co gamma-ray exposure by at most 20 percent at both irradiation distances and depths, while that of lithium-borate element 1 leads to an underestimation of beta-particle dose by ~60 percent, because of insufficient buildup in the 23 mg/cm^2 "open-window" layer of plastic. The lead filtration over the calcium-sulfate elements (elements 3 and 4) causes the absorbed dose to be underestimated by a factor of ~30.

Response to ^{204}Tl beta particles (E_{max} = 763 keV). At the 30-cm source-to-dosimeter distance, the beta particles are seen to penetrate only the "open-window" shield of the lithium-borate element 1 (23 mg/cm^2 of plastic), giving a beta-particle dose interpretation that is within 20 percent of the ^{60}Co gamma-ray exposure interpretation at a 7 mg/cm^2 depth in water.

Response to ^{147}Pm beta particles (E_{max} = 225 keV). After traversal of 20 cm of air, the beta particles are not sufficiently energetic to penetrate to any of the dosimeter elements.

6.5 Response to Gaseous Beta Emitters

Procedure

The experiment was performed four times. Each time, six individually characterized dosimeters, encased in cellophane wrappers, were suspended by a copper wire along the central axis of the immersion chamber, not more than 20 cm below the plane of the hood. For the first two experiments, the ^{133}Xe gas was introduced after deployment of the dosimeters, while for the experiments 3 and 4 the dosimeters were deployed 1 minute after the ^{133}Xe gas had been introduced, and the readings of the survey instruments, which were to be studied along with the personnel dosimeters, had stabilized. The dosimeter irradiation ended with their removal from the chamber and the removal of their cellophane wrappers. The grab samples of the chamber atmosphere taken during the four immersions indicated that there had been no substantial xenon loss during the periods of immersion.

The immersion times were chosen so that the resulting products of activity concentration times time ranged from 3.0×10^8 to 1.6×10^{11} pCi h m^{-3}. The corresponding values for absorbed dose to air and for the total dose equivalent were deduced from these values by means of the conversion factors for semi-infinite clouds given in Appendix B, Models for Calculating Doses from Noble Gases Discharged to the Atmosphere, of NRC Regulatory Guide 1.109 [8]. The conversion factors consisted of a beta term, taken directly from Table B-1 of the Guide, and a gamma term, for which a geometric correction factor for K x rays and 81-keV gamma rays was applied. For absorbed dose to air, the value of the total conversion factor was 1.201×10^{-7} mrad m^3/pCi h, consisting of a beta term of 1.198×10^{-7} and a gamma term of 3.4×10^{-10} mrad m^3/pCi h. For the dose equivalent, the total conversion factor was 3.51×10^{-8} mrem m^3/pCi consisting of a beta term (conversion to shallow dose equivalent) of 3.42×10^{-8} and a gamma term (conversion to total-body dose equivalent) of 9.5×10^{-10} mrem m^3/pCi h.

Table A-21 shows the results of the experiments, expressed in terms of the factor with which one has to multiply the interpretations of the TLD response in terms of perpendicularly incident ^{60}Co gamma radiation in order to obtain interpretations in terms of absorbed dose to tissue (i.e., in terms of the total dose equivalent) in a semi-infinite cloud. Since all but element 1 are shielded by filtration in front and back of the dosimeter, it is reasonable to consider here only the results obtained with element 1.

The results of experiments 1 and 2 are seen to be quite erratic. They are included in the table only in order to demonstrate the difficulty that may arise when calibrations are attempted before the activity is uniformly distributed in the immersion chamber. The results of experiments 3 and 4 agree well, indicating that the response of lithium borate in terms of dose equivalent in a uniform semi-infinite cloud may be obtained by dividing by five the exposure interpretation obtained from the response of the lithium-borate element 1 in a plane-parallel ^{60}Co gamma-ray beam, incident perpendicularly to the dosimeter surface.

Table A-21. Conversion Factors from Dosimeter Response in Terms of ^{60}Co Gamma-ray Exposure to Response to Simulated Semi-infinite ^{133}Xe Cloud in Terms of Absorbed Dose to Tissue

Experiment Number	Concentration of ^{133}Xe $pCi \cdot m^{-3}$	Dosimeter Immersion Time h	Absorbed Dose to Tissue mrad	Conversion Factor			
				Element 1	Element 2	Element 3	Element 4
1	1.56×10^{8}	2*	11.0±0.3	0.81±0.19	0.24±0.27	0.18±0.06	0.18±0.06
3	3.654×10^{8}	2	25.7±0.6	0.20±0.12	<0.01	<0.01	<0.01
2	9.208×10^{8}	17.86*	5780±120	0.43±0.02	0.01±0.15	0.05±0.08	0.03±0.04
4	2.160×10^{10}	1.98	1505±30	0.22±0.12	0.01±0.45	0.02±0.06	0.02±0.15

*Dosimeters deployed prior to breaking of ampoules containing ^{133}Xe.

6.6 Measurement Assurance Test for the NRC Region-1 Laboratory

This test was carried out in the form of an "intercomparison". Both NBS and the NRC Region-1 laboratory calibrated 50 Panasonic 802-AQ dosimeters for use in this test in four separate batches of roughly equal numbers of dosimeters. The dosimeters in one batch remained unexposed; the dosimeters in each of the other three batches received identical ^{137}Cs gamma-ray exposures in the range between 20 and 100 mR, each batch being assigned a different exposure level. Then the laboratories exchanged one-half of the dosimeters in each batch, for readout and exposure interpretation along with the dosimeters that had remained in the laboratory of their origin. Table A-22 shows the results of this study,

obtained from the calcium-sulfate dosimeter elements, which are altogether more reliable than the lithium-borate elements. The NRC exposure assignment and interpretation is seen to be approximately four percent higher (somewhat more at the lowest exposure level) than those of NBS. This may be explained on the basis of the larger contribution of low-energy, essentially isotropic, scattered radiation to the exposure delivered by the NRC panoramic source than to that delivered by the NBS beam source. The calcium-sulfate dosimeter elements are particularly sensitive to this radiation (see, e.g., tables A-11 and A-12).

Table A-22. Intercomparison, NRC-NBS ^{137}Cs Gamma-Ray Exposure Interpretation

Batch Origin	Exposure Assigned by Lab. of Origin mR	Exposure Interpretation by Readout Lab.* mR	Difference, $(X_{NRC}-X_{NBS})/X_{NBS}$ %
NRC	20.6	19.7 ± 0.3	+4.6
NRC	48.5	46.7 ± 0.6	+3.9
NRC	80.0	77.8 ± 1.2	+2.8
NBS	21.6	23.1 ± 0.6	+6.9
NBS	40.0	41.7 ± 0.9	+4.3
NBS	80.0	83.4 ± 2.2	+4.3

*Average and standard deviation from average for all dosimeters in a given batch.

6.7 Long-Term Physical Stability of Dosimeters Submitted to Repeated Use

The same set of 300 dosimeters was used throughout the entire study covered by this report. Except for the dosimeters submitted to conditions of very high temperatures and relative humidities (Section 5.3) or to "wet" conditions (Section 5.7), none of the dosimeters showed any signs of physical failure, such as loss of contact between the heat-absorbing surface and the phosphor--a condition that had been observed by the Nuclear Regulatory Commission's Region-1 laboratory and subsequently also by the manufacturer. In order to spot the first signs of such a "bubbling" problem, it is recommended to run glow curves routinely, since any reduction of phosphor heating due to loss of contact would be reflected in a displacement of the glow curve.

7. Conclusions and Recommendations

7.1 Summary of Test Results

Results of the tests conducted in accordance with ANSI N545-1975 are summarized in Table A-23. An indication of failure for any particular characteristic tested does not necessarily mean that all pertinent performance specifications were unsatisfied. This is particularly true when the performance requirement was stated over a broad range, such as energy dependence. Failure to meet performance specifications over only a small part of the range would necessarily mean failure of the test for that characteristic, even though performance was satisfactory over most of the range. The dosimeter may perform adequately in an application where the range of interest is narrower than that stated in the ANSI N545-1975 performance specifications. The reader should keep this in mind when observing the gross results indicated in Table A-23, and should refer to the indicated references for more detailed interpretation of the test results.

Table A-23. Summary of Test Results (ANSI N545-1975)

Characteristic Tested	Reference in This Report	Reference in ANSI N545	Dosimeter Performance* Determined by: lithium-borate element 1	lithium-borate element 2	calcium-sulfate elements
uniformity	5.1	3.1	P	P	P
uniformity	5.1	4.3.1	F	F	P
reproducibility	5.2	4.3.2	F	F	P
length of field cycle	5.3	4.3.3	F	F	P
energy dependence	5.4	4.3.4	F	F	F
directional dependence	5.5	4.3.5	F	F	F
light dependence	5.6	4.3.6	F	F	P
moisture dependence	5.7	4.3.7	F	F	P
self-irradiation	5.8	4.3.8	P	P	P

*P - passed all performance specifications for the characteristic tested.
F - failed to pass all performance specifications for the characteristic tested.

For those tests that went beyond ANSI N545-1975 (Section 6 of this part), no performance specifications exist that were developed using a consensus process. The test for directional dependence, using discrete angles of radiation incidence, showed a pronounced over-response by the calcium-sulfate elements for lateral incidence of low-energy radiation (see 6.1). It was also shown that dosimeter response will be drastically reduced if the dosimeters are shielded by a supporting pole. The salt-spray test, using performance specifications

similar to those for dependence on the length of the field cycle (ANSI N545-1975, Section 4.3.3), showed that the test was passed easily when the calcium-sulfate elements were used for the evaluation, passed when lithium-borate element 2 was used, but failed for element 1. No effect on dosimeter response was evident when the drop test was performed. The study of dosimeter response to beta-particle sources showed that the calcium-sulfate elements cause the absorbed dose to be underestimated by a factor of about 30, for even the highest energy betas (2.28 MeV) used in the study. The lithium-borate elements respond considerably better, but show a strong dependence on beta-particle energy (see 6.4 for details). When immersed in a semi-infinite cloud of xenon-133 gas, only the lithium-borate element 1 responded significantly. Its response in terms of dose equivalent may be obtained by multiplying by 0.2 the exposure interpretation obtained for cobalt-60 gamma radiation (see 6.5).

7.2 Conclusions Based on Test Results

The test results support a number of conclusions. As mentioned earlier, such conclusions must be balanced against the requirements for a particular application of a dosimetry system. Those requirements may, or may not, be equivalent to the performance specifications used in the tests reported in this document.

As shown in Table A-23, the dosimeter fails to meet ANSI N545 performance specifications, regardless of which element is used to determine performance, for two characteristics--energy dependence and directional dependence. Recommendations for improving both of these characteristics are given in 7.3.

Performance of the lithium-borate elements is inferior to that of the calcium-sulfate elements for a majority of the test characteristics. The obvious exception is response to beta particles, in which case the lithium-borate elements demonstrate the better performance. Liquefaction of the lithium-borate elements under conditions of high humidity and temperature, and the consequent loss of readout information, may present operational problems. At the least, it represents a deployment limitation that must be considered. (See 5.3 and 5.7.)

7.3 Recommendations

The test results, and the conclusions based on those results, lead to several specific recommendations that should be considered.

In Section 5.2, it is shown that all dosimeters consistently fail the test for reproducibility when performance is determined from the lithium-borate elements. As a result, it is recommended that these elements not be relied on when good reproducibility is required for readings at levels close to natural background.

The test for energy dependence (Section 5.4) resulted in the failure of the calcium-sulfate elements to meet performance specifications for energies in the range of 80 keV to 1.25 MeV. This led to the recommendation that the filtration of these elements be replaced by filtration resulting in less attenuation of the incident radiation.

Results of the tests of directional dependence (Sections 5.5 and 6.1- indicate a failure of the calcium-sulfate elements to pass the performance specifications, particularly at lower photon energies. It is therefore recommended that the response of these elements be improved through judicious lateral shielding by a high-atomic number material incorporated into the holder (possibly in the form of a sleeve around the phosphor support, taking the place of the present brass sleeve).

PART B

CHARACTERIZATION OF SURVEY INSTRUMENTS

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PART B

CHARACTERIZATION OF SURVEY INSTRUMENTS

1. Characterization of Radiation Beams

1.1 Photon Beams

1.1.1 Bremsstrahlung

This section deals with the spectrometry of the NBS bremsstrahlung beams that were used for instrument calibration during most of the period of the inter-agency agreement covered by this report. During the third year of the agreement, after the studies of most of the radiation-survey instruments had been completed, the NBS Center for Radiation Research had a new x-ray machine installed, which extended the range of available constant potentials to 300 kV. At that time, some of the bremsstrahlung beams used formerly were discontinued and some new ones were added. The adaptations required for spectrometry with the new machine are not as yet available.

Pulse-height distributions were obtained with a high-resolution intrinsic germanium spectrometer for exciting potentials in the range from 10 to 250 kV, and were unfolded using detector response functions and unfolding procedures developed at NBS.[9] Figures B-1 through B-9 show the final spectra. The delta functions drawn in Figures B-1 through B-5 (straight lines with arrows) represent the characteristic K-fluorescence x-ray lines stemming from the tungsten target and the lead filtration in the beams; they were separated from the continuum portion of the spectra, along with extraneous lines, produced in some cases by the gold pinhole collimator used in the experiments, which were discarded. The percentage contribution of the characteristic tungsten and lead K-shell x-ray lines to the total number of photons in the beam are shown in Table B-1. For the spectra produced at constant potential between 15 and 30 kV, there also was a small contribution from characteristic tungsten L-shell x-ray lines, which is shown in Table B-2, but was not plotted in Figures B-8 and B-9. The discontinuities in the continuum portion of some of the spectra are due to the photon absorption edges of the target or the lead filtration (tungsten K-edge at 69.5 keV, lead K-edge at 88.0 keV).

As a check on the consistency of the unfolding procedure, half-value layers were obtained from the appropriate integrals over the unfolded spectra. Table B-3 shows a comparison of the aluminum and copper half-value layers and homogeneity coefficients obtained from attenuation measurements [7] with those derived from the unfolded spectra. There generally is agreement to within ±5 percent, which is well within the uncertainties in the values calculated from the spectra. Only for the low-energy, lightly filtered beams, does the difference between the values obtained from the attenuation measurements and those calculated from the spectra tend to be larger. This is qualitatively compatible with the larger distance (400 cm) and consequently higher air filtration for the spectral measurements as compared with the 50-cm distance used for the attenuation measurements.

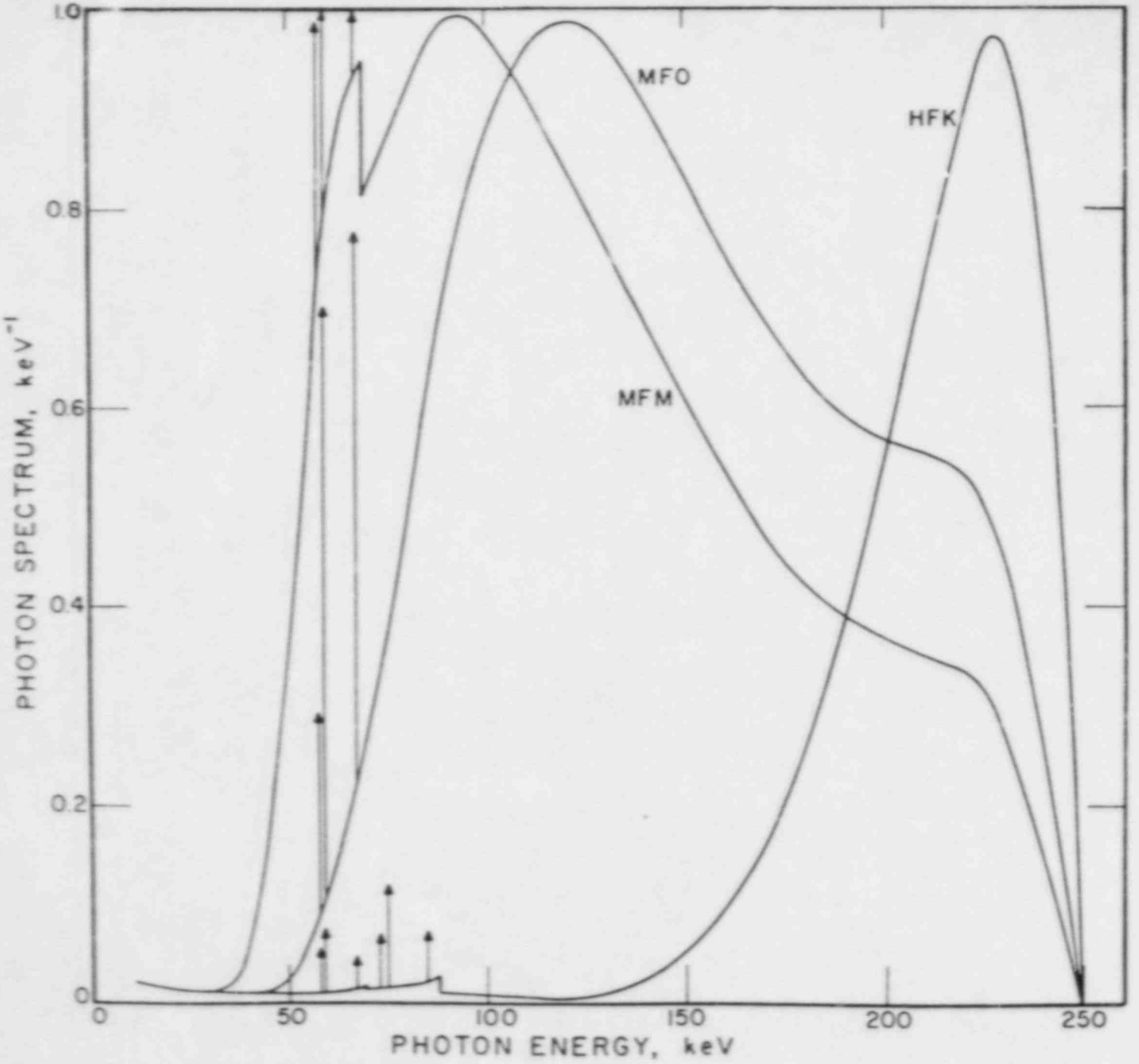


Figure B-1 NBS Bremsstrahlung Spectra, Old Codes: HFK, MFO, and MFM (Approximately Corresponding to New Codes: H250, M250, and none).

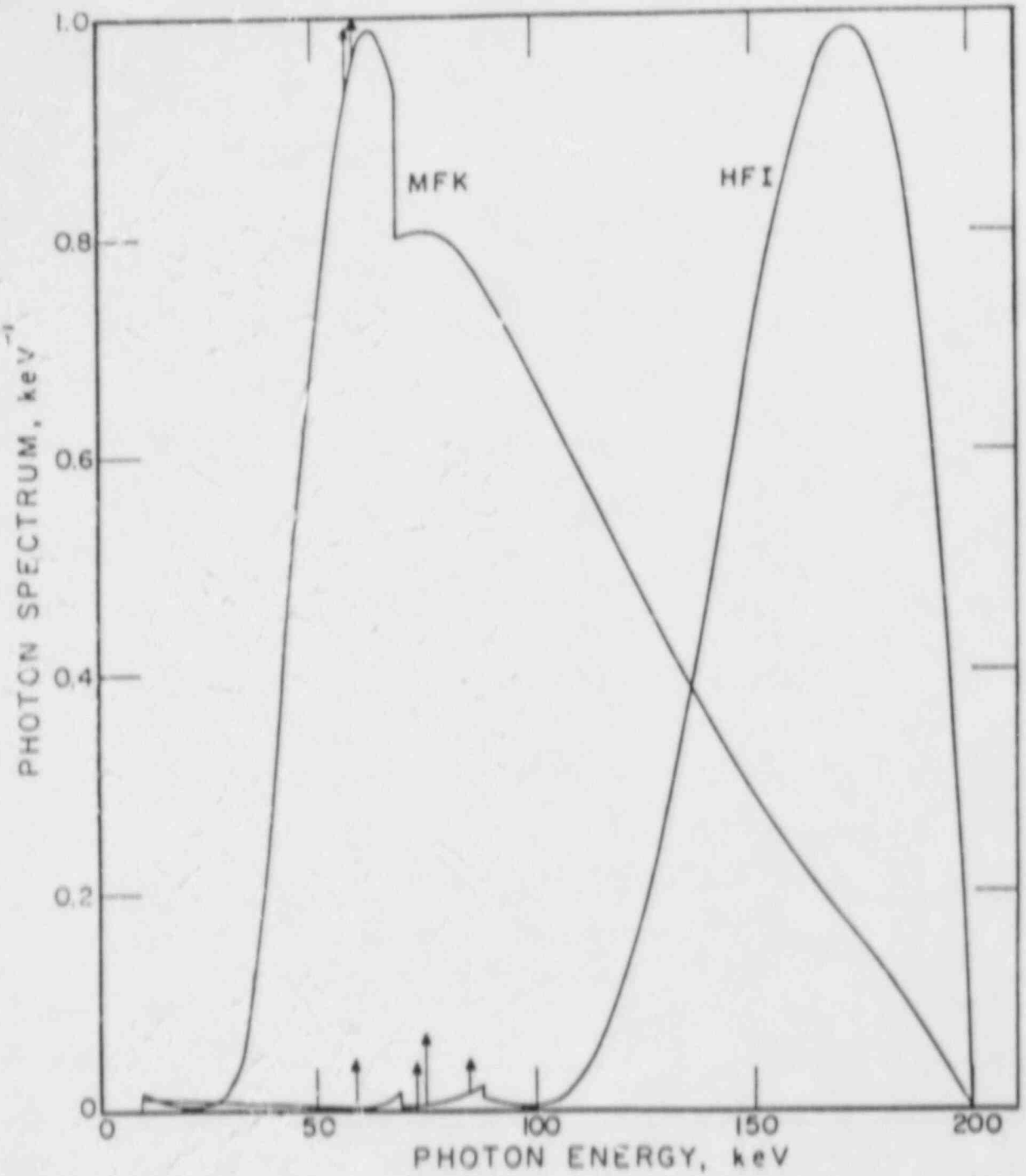


Figure B-2 NBS Bremsstrahlung Spectra, Old Codes: HFI and MFK (Approximately Corresponding to New Codes: H150 and M150).

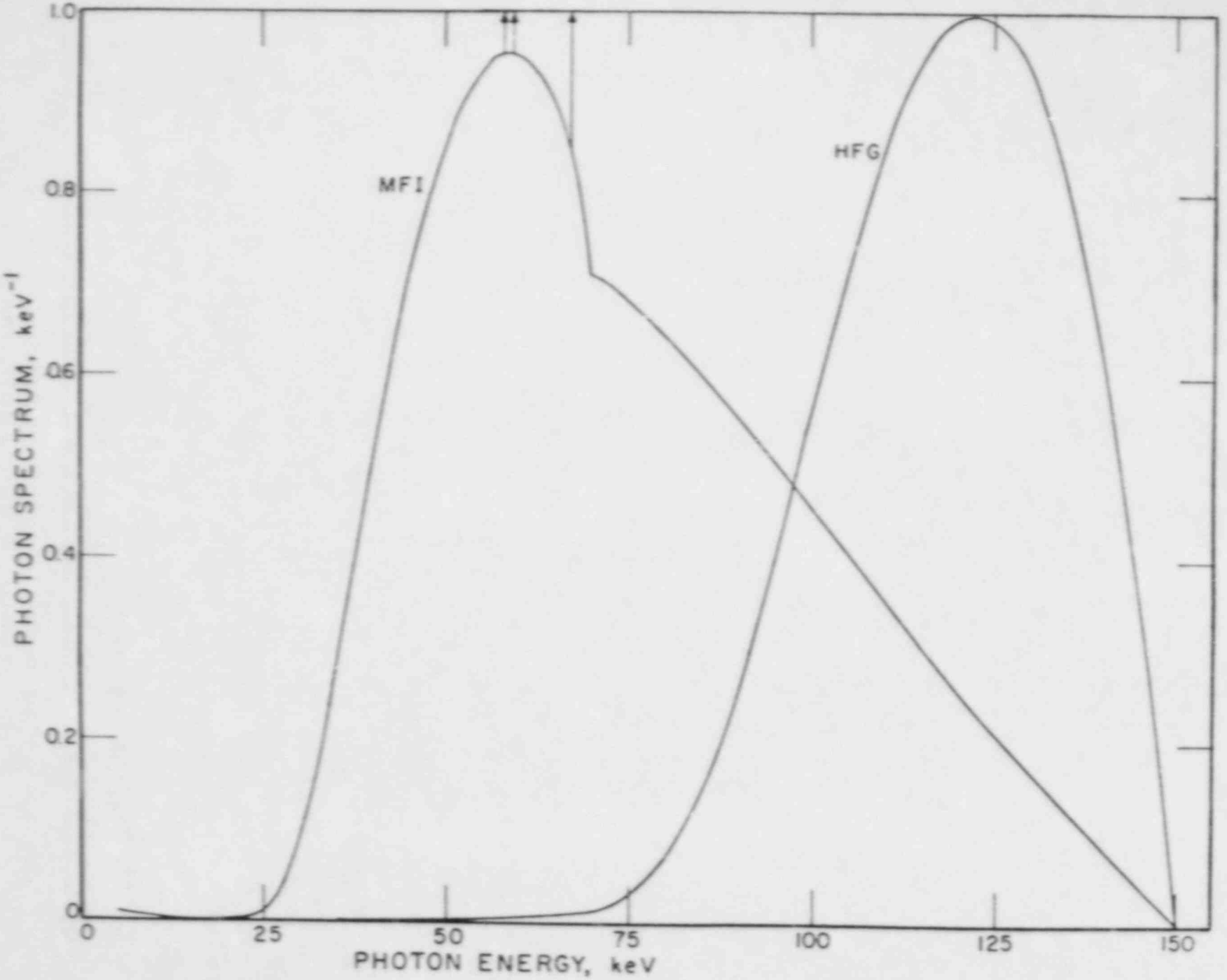


Figure B-3 NBS Bremsstrahlung Spectra, Old Codes: HFG and MFI (Approximately Corresponding to New Codes: H150 and M150).

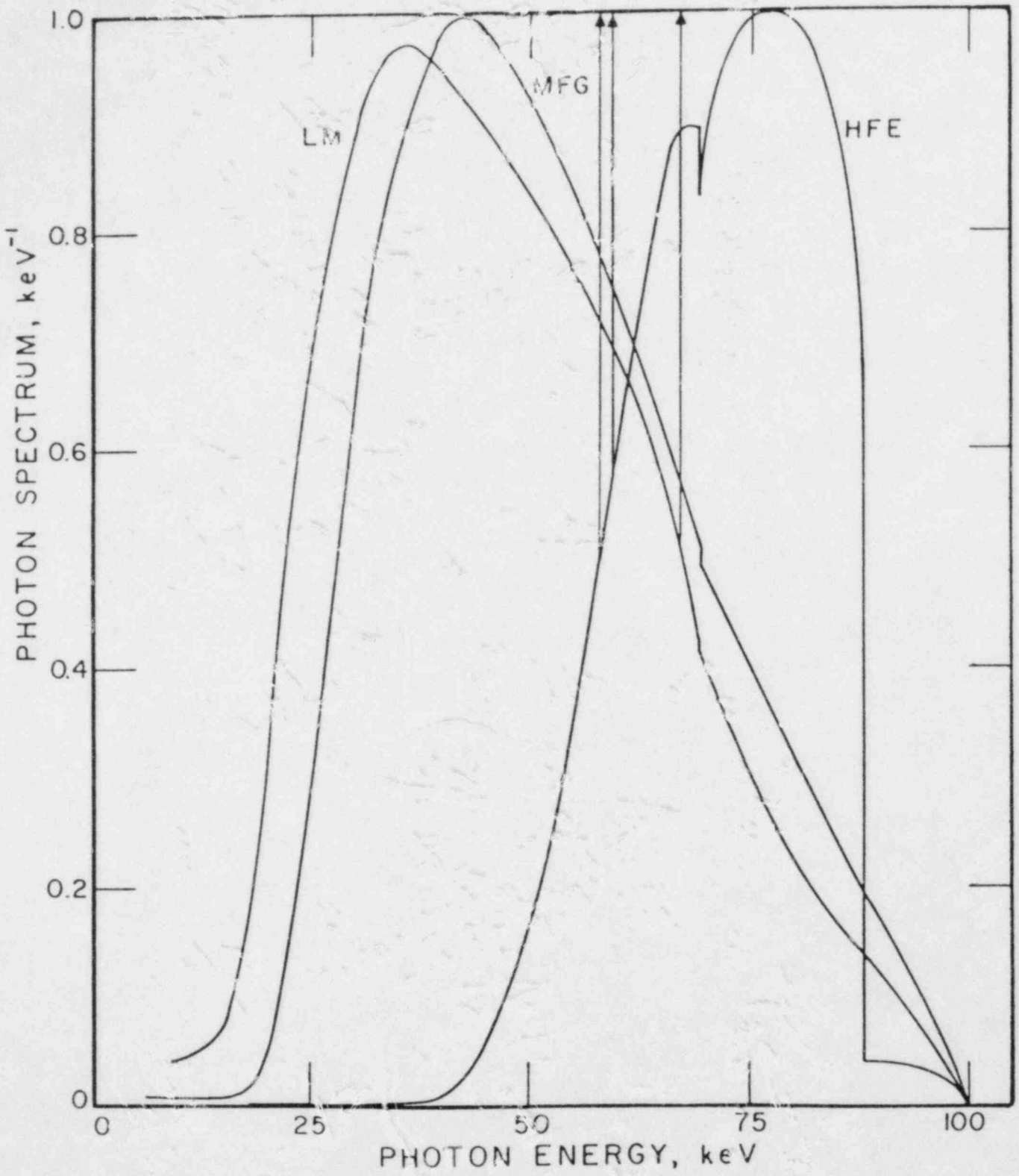


Figure B-4 NBS Bremsstrahlung Spectra, Old Codes: HFE, MFG, and LM (Approximately Corresponding to New Codes: none, M100, and L100).

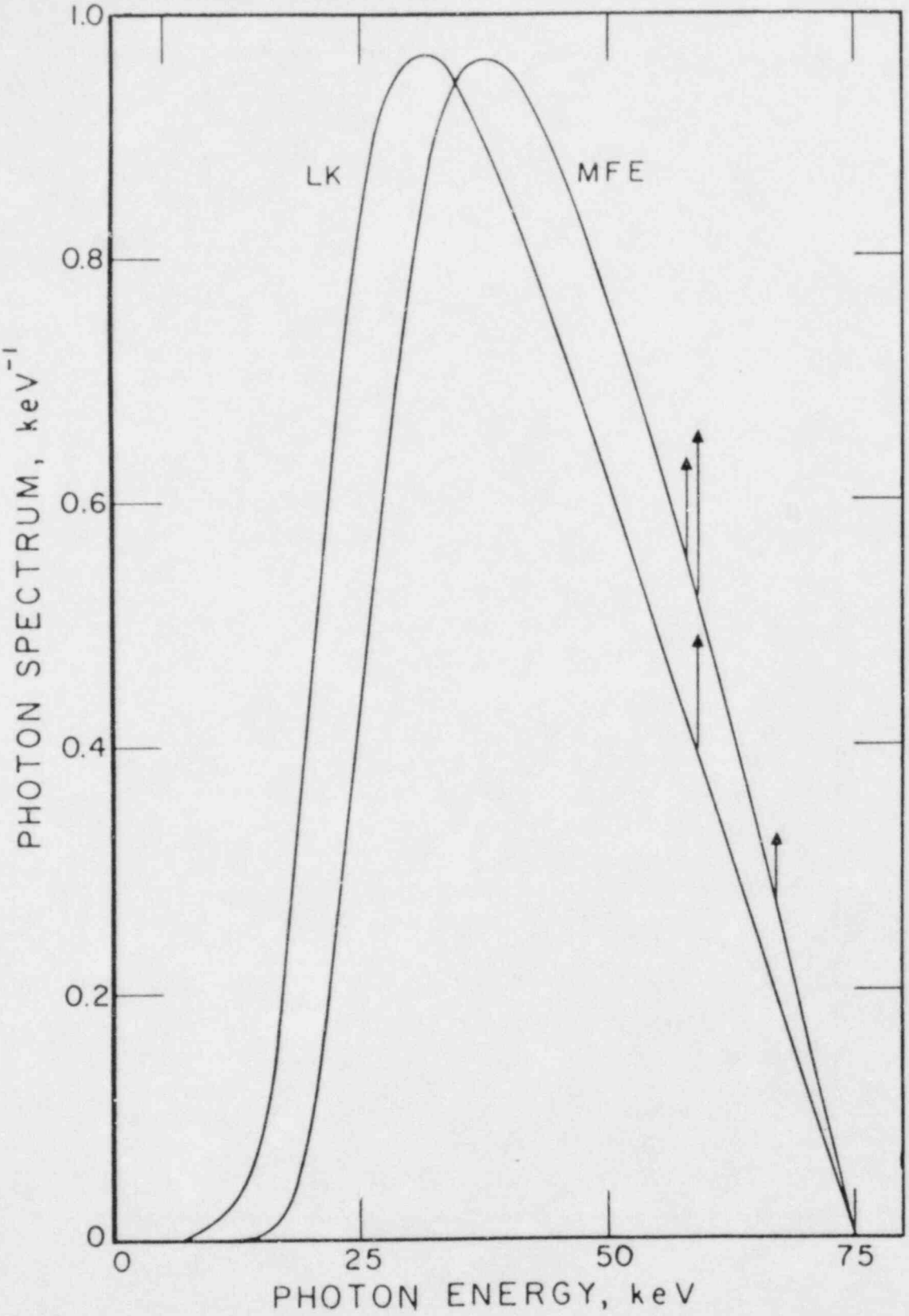


Figure B-5 NBS Bremsstrahlung Spectra, Old Codes: MFE and LK (Approximately Corresponding to New Codes: none, and S75).

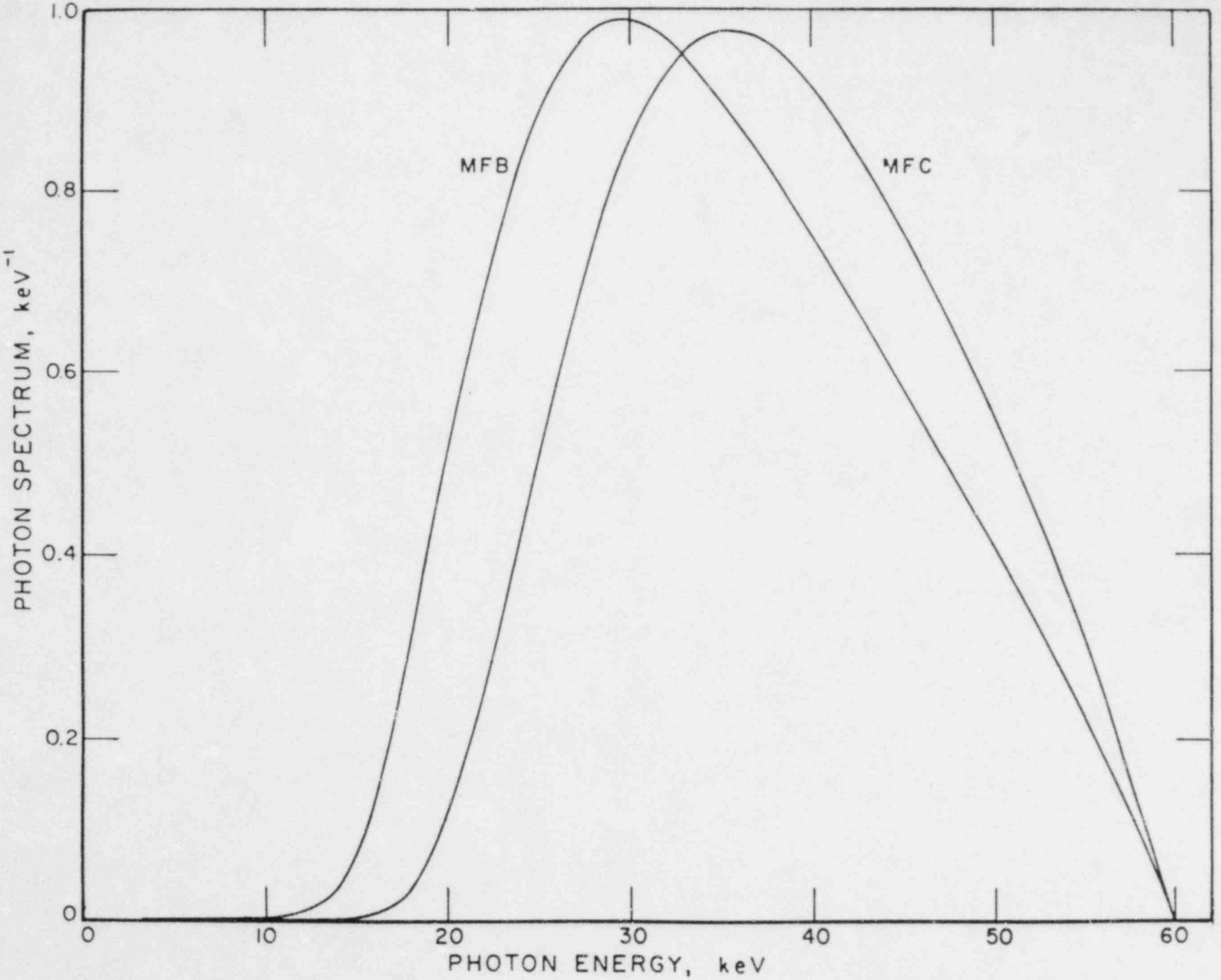


Figure B-6 NBS Bremsstrahlung Spectra, Old Codes: MFC and MFB (Approximately Corresponding to New Codes: S60 and M60).

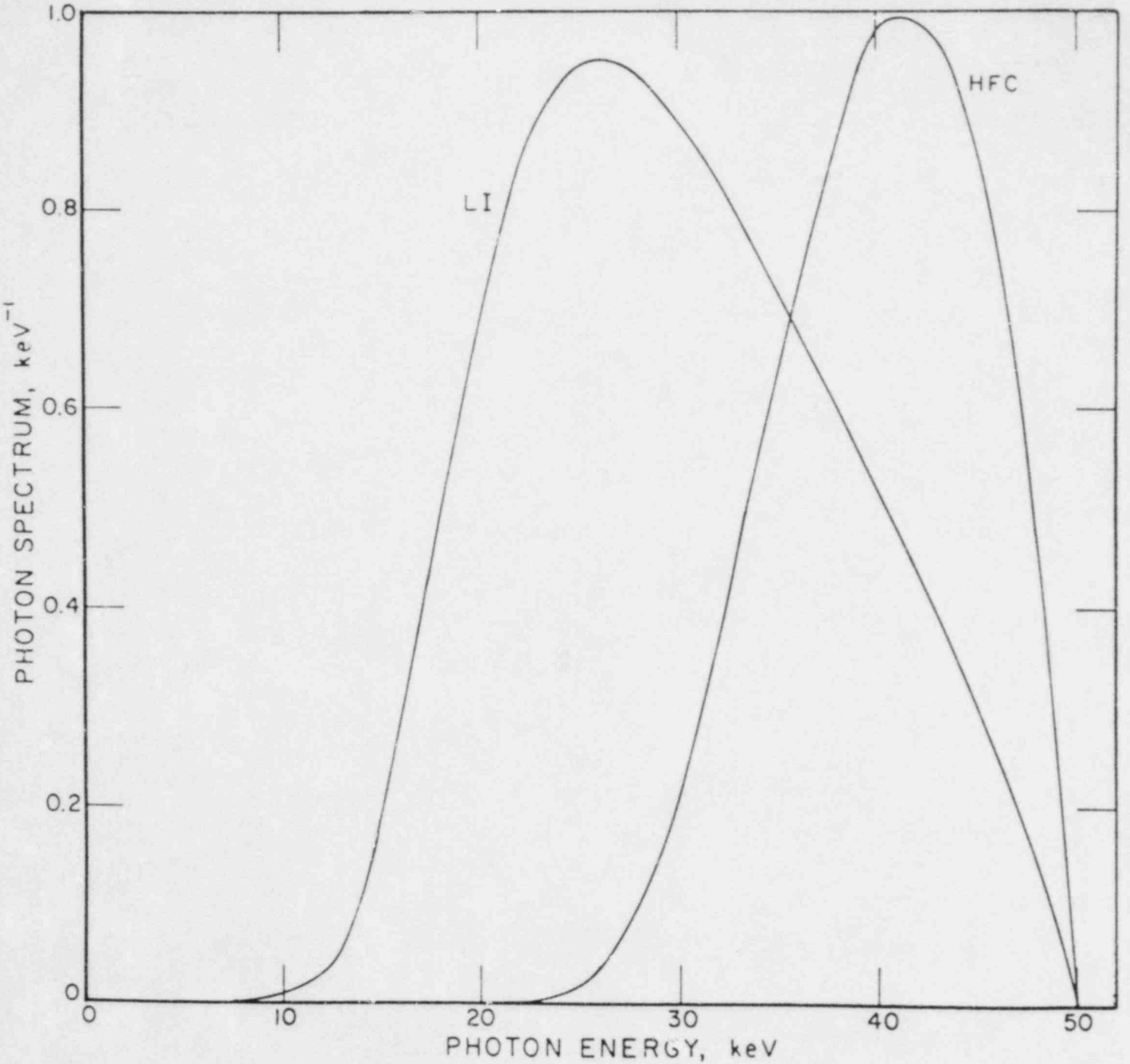


Figure B-7 NBS Bremsstrahlung Spectra, Old Codes: HFC and LI (Approximately Corresponding to New Codes: H50 and M50).

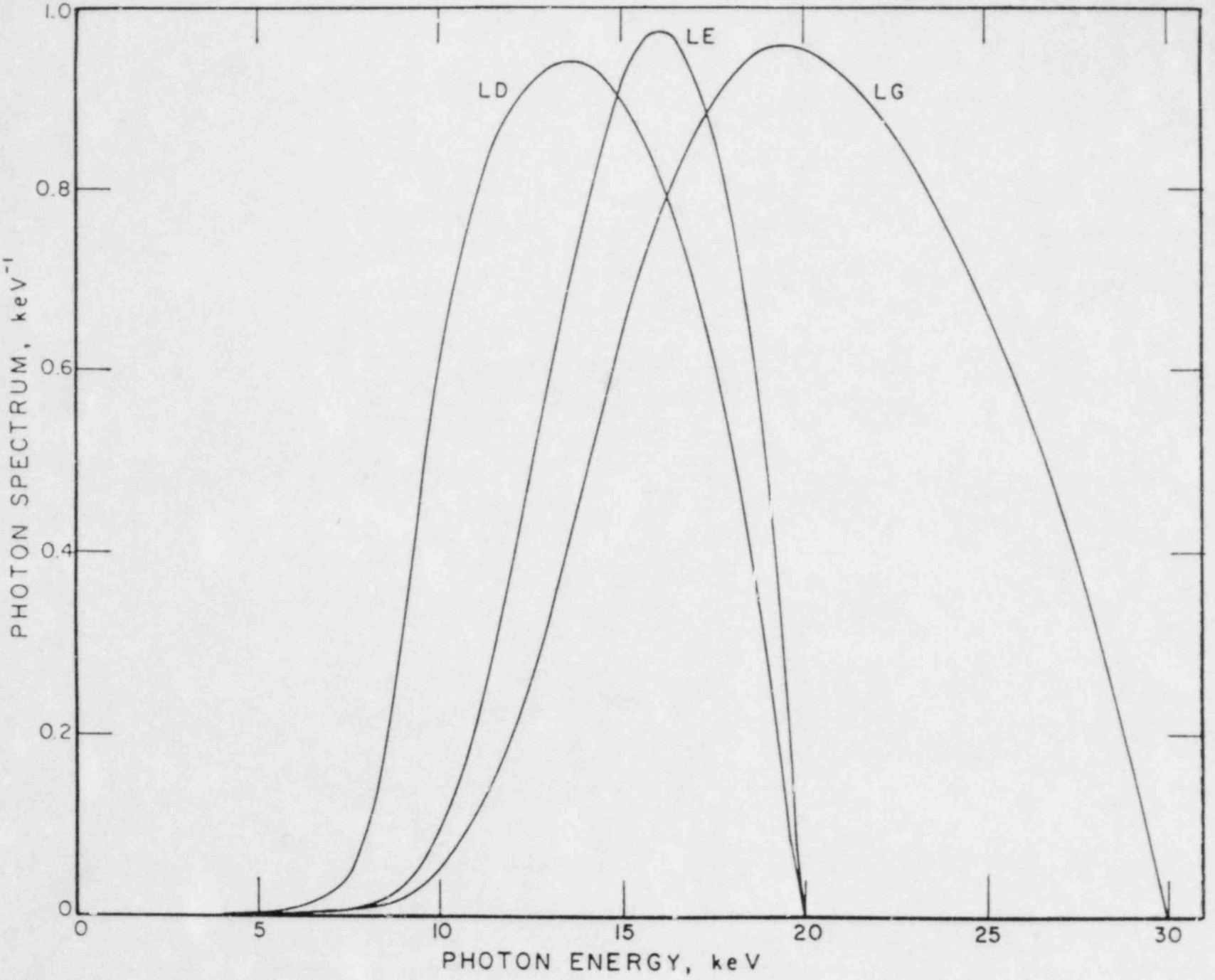


Figure B-8 NBS Bremsstrahlung Spectra, Old Codes: LG, LE, and LD (Approximately Corresponding to New Codes: M30, none, and L20).

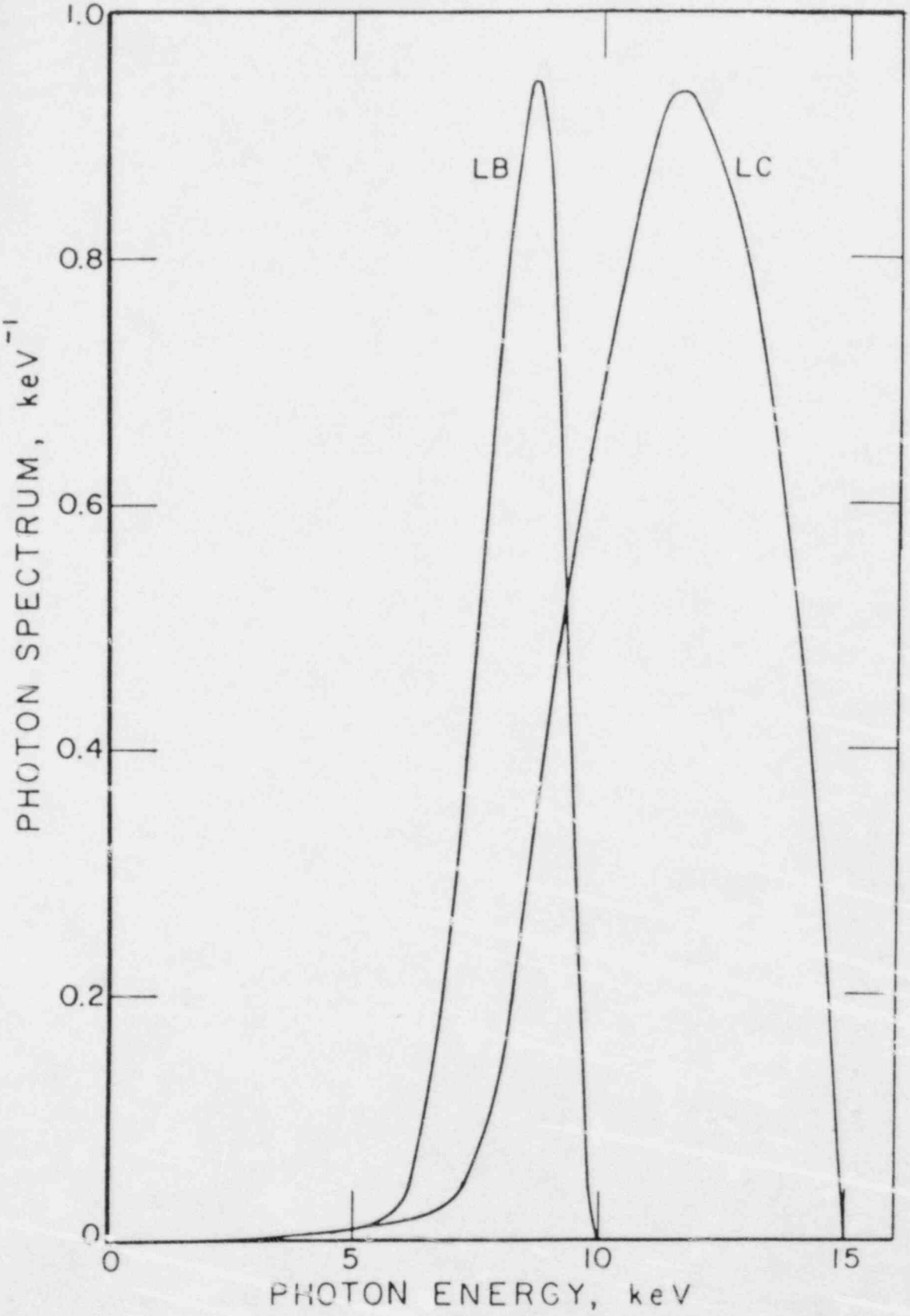


Figure B-9 NBS Bremsstrahlung Spectra, Old Codes: LC and LB (Approximately Corresponding to New Codes: L15 and L10).

Table B-1. Contribution of Characteristic Tungsten and Lead X-Rays to NBS Bremsstrahlung Beams Used for Instrument Calibration

NBS Beam Code		Constant Potential	Percent Contribution of Characteristic X-Ray Lines					
			57.982 keV	59.318 keV	67.152 keV	72.804 keV	74.969 keV	84.78 keV
New[1]	Old	(kV)	($WK\alpha_2$)	($WK\alpha_1$)	($WK\beta_{1,3}$)	($PbK\alpha_2$)	($PbK\alpha_1$)	($PbK\beta_{1,3}$)
H250	HFK	250	0.1	0.1	0.1	0.1	0.2	0.1
M250	MFO	250	0.1	0.5	0.4			
--	MFM	250	2.2	4.3	2.1			
H200	HFI	200	--	0.0	--	0.1	0.1	0.0
--	MFK	200	3.6	6.9	2.7			
H150	HFG	150	--	0.0	0.0			
M150	MFI	150	3.9	7.0	2.6			
--	MFE	100	1.8	3.9	2.5			
M100	MFG	100	2.9	3.7	1.2			
L100	LM	100	1.5	2.7	0.8			
--	MFE	75	0.1	0.1	0.1			
--	LK	75	--	0.3	--			

[1]Added for convenience. Work was performed prior to introduction of new code.

Table B-2. Contribution of Characteristic Tungsten X-Rays to NBS Bremsstrahlung Beams Used for Instrument Calibration

NBS Beam Code		Constant Potential (kV)	Percent Contribution of Characteristic X-Ray Lines		
New[1]	Old		8.4 keV ($WL\alpha$)	9.7 keV ($WL\beta$)	11.3 keV ($WL\gamma$)
S60	MFC	60	--	--	--
M60	MFB	60	--	--	--
H50	HFC	50	--	--	--
M50	LI	50	--	--	--
M30	LG	30	--	0.4	0.4
--	LE	20	0.4	0.8	0.4
L20	LD	20	5.5	10.3	2.1
L15	LC	15	6.9	11.2	3.0
L10	LB	10	--	--	--

[1]Added for convenience. Work was performed prior to introduction of new code.

Table B-3. Comparison of Half-Value Layers and Homogeneity Coefficients for Selected NBS Bremsstrahlung Beams Obtained from Attenuation Measurements with Those Calculated from Photon Spectra

NBS Beam Code		Constant Potential	Half-value Layer				Homogeneity Coefficient[4]	
			Measured[2]		Calculated[3]			
New[1]	Old	(kV)	Cu (mm)	Al (mm)	Cu (mm)	Al (mm)	Meas.	Calc.
H250	HFK	250	5.25	21.6	5.19	20.9	--	0.96
M250	MFO	250	3.25	18.3	3.48	18.6	0.98	0.96
--	MFM	250	2.23	15.8	2.44	16.4	0.92	0.92
H200	HFI	200	4.09	19.6	4.04	19.3	--	0.97
--	MFK	200	1.24	13.2	1.25	13.3	0.92	0.89
H150	HFG	150	2.45	17.0	2.35	16.3	--	0.94
M150	MFI	150	0.66	10.3	0.61	9.71	0.89	0.81
--	HFE	100	0.74	11.2	0.[illegible]	10.[illegible]		0.88
M100	MFG	100	0.20	5.03	0.20	4.93	0.	0.69
L100	LM	100	--	2.78	0.091	2.71	0.59	0.51
--	MFE	75	0.12	3.39	0.11	3.33	0.74	0.68
S75	LK	75	--	1.86	0.064	2.04	0.63	0.59
S60	MFC	60	0.090	2.79	0.088	2.77	0.79	0.74
M60	MFB	60	--	1.62	0.051	1.67	0.68	0.64
H50	HFC	50	0.14	4.19	0.14	4.15	--	0.88
M50	LI	50	--	1.02	0.037	1.22	0.66	0.66
M30	LG	30	--	0.36	0.016	0.49	0.64	0.69
--	LE	20	--	0.23	0.009	0.27	0.78	0.76

[1]Added for convenience. Work was performed prior to introduction of new code.

[2]From attenuation measurements at a distance of 50 cm.

[3]From spectra obtained from measurements at a distance of 400 cm.

[4]Ratio of first Al HVL to second Al HVL.

1.1.2 Gamma Radiation

One each of the relatively low-output collimated horizontal-beam ^{137}Cs and ^{60}Co gamma-ray sources were used for most of the instrument studies described in this report. These sources were supplemented by a low-output ^{137}Cs gamma-ray source used free in air in a 4π geometry.

Spectrometry is difficult on these types of sources, since even the relatively low-output sources used for protection-level instrument calibrations are too intense for direct spectrometry, and it therefore becomes necessary either to use a simulated source of the same geometry with much reduced radiation output, or to deduce the initial spectrum of the source from spectral measurements in a Compton-scattered beam. So far, spectrometry has been performed on only one of the NBS (vertical-beam) ^{60}Co gamma-ray sources.[10,11] It was found that, for a field size of 25cm x 25cm at a distance of 1 meter, 6.5 percent of the total exposure stemmed from radiation of photon energies less than 800 keV.[11] (The corresponding number for a 5cm x 5cm field size at a distance of 1 meter was ~4%.) It is expected that the scatter contribution to exposure is comparable or smaller for the other collimated beams (particularly those from sources of low output). For the ^{137}Cs gamma-ray source that was used in 4π geometry, the contribution to exposure from room- and air-scattered radiation is discussed in Section 2.2 of this report.

1.1.3 ~6.5-MeV Photons

The objective was to provide, for the study of the radiation-protection instruments, a photon spectrum close to the one present in the vicinity of power reactors as a consequence of the activation of water by fast neutrons. For this purpose, essentially monoenergetic photons of energies 6.1, 6.9, and 7.1 MeV were produced in the NBS positive-ion Van de Graaff accelerator in the nuclear reaction, $^{19}F(p,\alpha\gamma)^{16}O$, by having protons of an energy of ~2 MeV impinge upon a ~6 mg/cm^2 CaF_2 target. A similar setup had been used earlier by the National Research Council of Canada [12].

Beam Diagnostics

Figure B-10 shows the pulse-height distribution obtained with an intrinsic Ge detector (active volume: ~60 cm^3; nominal resolution and efficiency at 1.25 MeV: ~15% and 2 keV, respectively), demonstrating that, in addition to the high-energy photons stemming from the nuclear reaction, there is some 0.511-MeV annihilation radiation present, as well as some photons of energies ≤0.2 MeV. The annihilation radiation could not be removed by either lead or steel filtration, since the filtration produced about as much annihilation radiation as it absorbed. This radiation, as well as the low-energy photon contamination, probably is present around power reactors, as well. There also was contamination of the beam by electrons, which was detected during the determination of absorbed-dose rate at the point of interest (see below), and was taken into account by an appropriate choice of the method for specifying dose rate in a phantom.

Beam diagnostics showed the inverse-square law to hold for distances ≥1 m from the target. Also, at a distance of 1 meter, beam uniformity over a circular area of ~30 cm in diameter was found to be adequate for instrument calibration, the fluence in a direction making an angle of ~22.5° with that of the beam axis being reduced by only ~10 percent relative to the on-axis fluence.

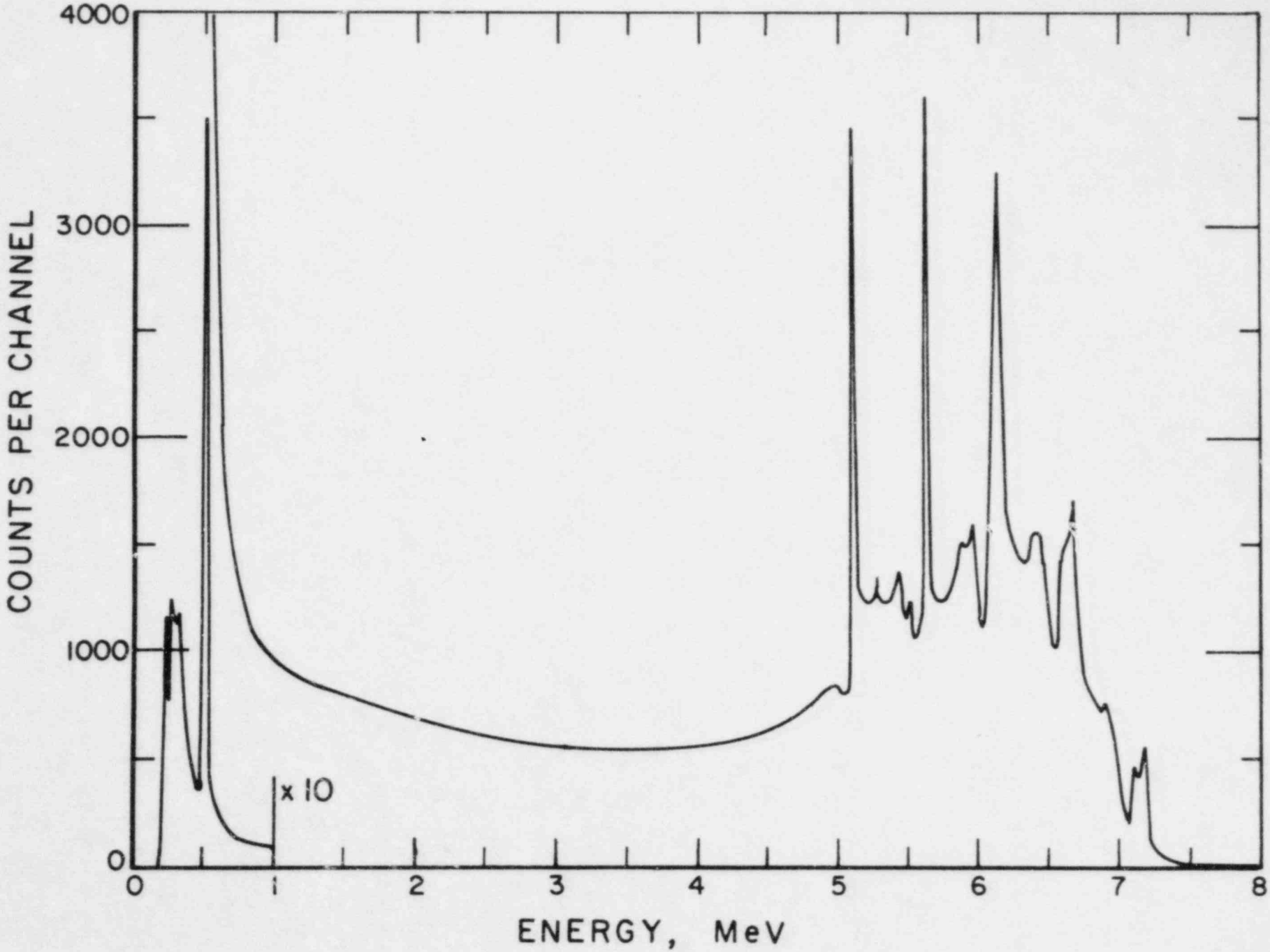


Figure B-10 Pulse-Height Spectrum of Photons Produced in the $^{19}F(p,\alpha\gamma)^{16}O$ Reaction.

Beam Dosimetry

The beam was standardized in terms of absorbed-dose rate to water as determined at a distance of 1 meter from the source in a 20cm x 20cm x 20cm Lucite phantom (which had been found to give the same results as a 30cm x 30cm x 30cm phantom). Because of the relatively low absorbed-dose rates of ≤30 mrad/h it was impossible to carry out the in-phantom measurements with a small ionization chamber--which would have been the instrument of choice. A thermoluminescence (TL) dosimetry system, employing LiF (TLD-100) samples, was used instead. Its sensitivity (dosimeter response per unit of absorbed dose to water) as measured in Lucite is known to be independent of photon energy for bremsstrahlung up to 25 MeV.[13] While at higher dose levels, the standard deviation of the system's response is ~1 percent for individually calibrated TL samples, it ranged from about 2 to 6 percent for the nine samples irradiated simultaneously at the various depths in the Lucite phantom at the low dose levels that had to be used in this study. TLD readings were related to beam output via either a plastic-scintillator system (Nuclear Enterprises 110 with associated electronics) or an ionization chamber (Exradin Model A6), used as the monitor.

Figure B-11 is a plot of the logarithm of corrected TL response per monitor unit as a function of depth in the Lucite phantom. The strong attenuation for depths up to ~2.5 cm in Lucite suggests contamination of the beam with electrons of energies below ~5.5 MeV. For larger depths, attenuation is seen to be exponential, a least-squares fit yielding a constant slope of -0.0141 ± 0.0047 for the straight line on the semi-log plot. It was therefore decided to choose a depth of 2.5 cm in the Lucite phantom for defining the absorbed-dose rate. Absorbed-dose rate to water at the same point was derived from the absorbed-dose rate to Lucite using data derived from absorbed-dose calorimetry.[13] The uncertainty in the determination of the absorbed-dose rate to water at the point of interest for instrument calibration is estimated to have an upper bound of ~10 percent.

1.2 Beta Particles

1.2.1 Beta-Particle Beams

The Amersham-Buchler beta-particle sources, which had been initially standardized at the Physikalisch-Technische Bundesanstalt (PTB) were used for instrument calibrations in beta-particle beams. (See Table B-4 for some of the source characteristics.)

Beam Diagnostics and Dose-Rate Checks

A number of preliminary measurements were performed with an extrapolation ionization chamber prior to putting the sources to use at NBS. Table B-5 shows the results of a check of the PTB dose-rate standardization. The agreement with the NBS measurements is seen to be satisfactory. The results of a check on the uniformity of the dose rate over the beam cross section is shown in Figure B-12. For $^{90}Sr/^{90}Y$ and ^{204}Tl, the dose rate is seen to vary by less than ±5 percent along a horizontal distance of ~20 cm. The variation over the same distance is somewhat larger for ^{147}Pm. Another set of results of interest is shown in Figure B-13, demonstrating how critical instrument positioning is in calibrations with beta-particle beams, particularly when the mean beta-particle energy is low (e.g., for the ^{147}Pm source).

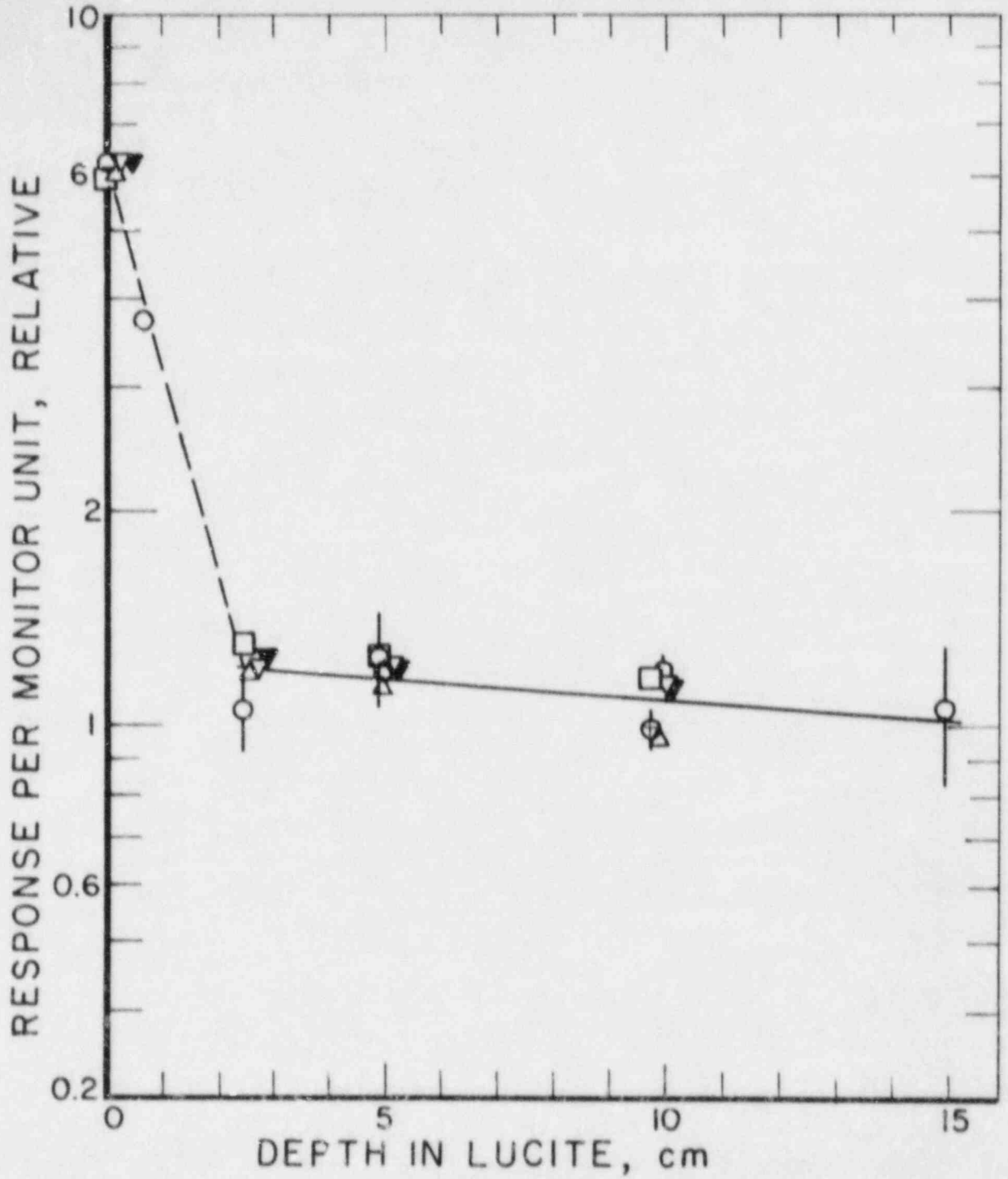


Figure B-11 Dependence of Corrected TL Response per Monitor Unit on Depth in a Lucite Phantom. While, for the experiment, the source-to-phantom-surface distance was maintained at 1 meter, the points shown here are for a constant source-to-detector distance of 1 meter. They were obtained from the measured data by an inverse-square correction. The different symbols represent data points measured on several separate days during two series of runs, one in the fall of 1982, the other in the summer of 1983. Different types of monitors at different locations were used for the two series. The data from the two series were fitted to each other by making their averages coincide. The open and solid symbols are for data obtained with cubical phantoms of 20-cm and 30-cm side lengths, respectively.

Table B-4. Amersham-Buchler Beta-Particle Sources

(a) Physical Characteristics of Sources Supplied to NBS

Type of Source and Appr. Half Life	Radioactive Element	Source Encapsulation	Nominal Activity, MBq(mCi); date
$^{90}Sr/^{90}Y$ 28.5y	^{90}Sr carbonate pressed[1] into Ag foil	50 mg/cm^2 Ag +0.1 mm steel	1850(50); May 24, 1982
$^{90}Sr/^{90}Y$ 28.5y	^{90}Sr carbonate pressed[1] into Ag foil	50 mg/cm^2 Ag +0.1 mm steel	74(2); Dec 16, 1982
^{204}Tl 3.78y	^{204}Tl pressed[1] into Ag foil	20 mg/cm^2 Ag	18.5(0.5); Dec 16, 1982
^{147}Pm 2.62y	^{147}Pm pressed[1] into Ag foil	5 mg/cm^2 Ag	518(14); Dec 16, 1982

(b) Beta-Particle Ranges

Type of Source	Avg. and Max. Beta-Particle Energies (MeV)[3]	Range in air		Range in plastic	
		cm	mg/cm^2	cm	mg/cm^2
^{90}Sr[2]	$\bar{E}$ = 0.196	41	49		
	E_{max} = 0.546	187	225	0.17	204
^{90}Y	$\bar{E}$ = 0.935	375	452		
	E_{max} = 2.284	1037	1249	0.98	1170
^{204}Tl	$\bar{E}$ = 0.244	58	70		
	E_{max} = 0.763	291	351	0.27	320
^{147}Pm	$\bar{E}$ = 0.062	59	7.2		
	E_{max} = 0.225	51	61	0.047	56

[1] During the rolling stage.

[2] Essentially, none of the beta particles from ^{90}Sr penetrate the combined filtration of (1) the source encapsulation, (2) the 10 cm of air, and (3) the beam-flattening filter.

[3] Average and maximum energies are for ideal point source.

Table B-5. Comparison of Absorbed-Dose Rates to Air Obtained by NBS and by PTB

Source		Absorbed Dose Rate			
			μGy/s*		
Type	Nominal activity (mCi)	At source-to-detector distance (cm)	NBS	PTB	Ratio, NBS/PTB
^{147}Pm	14	20	0.234	0.227	1.03
^{204}Tl	0.5	30	0.293	0.293	1.00
$^{90}Sr/^{90}Y$	2	30	1.707	1.685	1.01
"	50	11	451	449	1.01
"	"	30	62.4	61.9	1.01
"	"	50	22.4	22.2	1.01

*Referred to Jan. 1, 1983, 20°C, and 760 mm Hg.

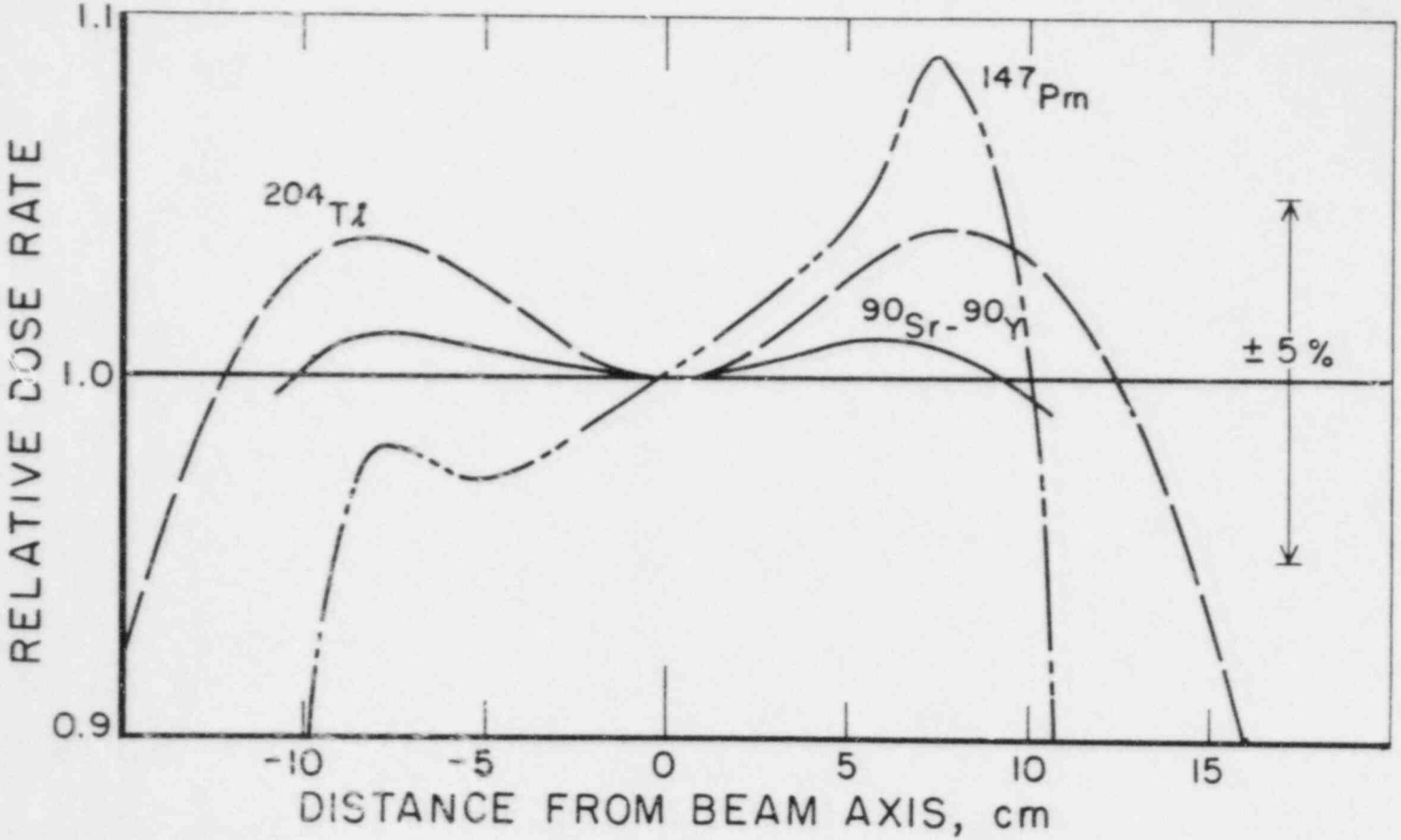


Figure B-12 Degree of Non-Uniformity of Beta-Particle Dose Rate over the Beam Cross Section.

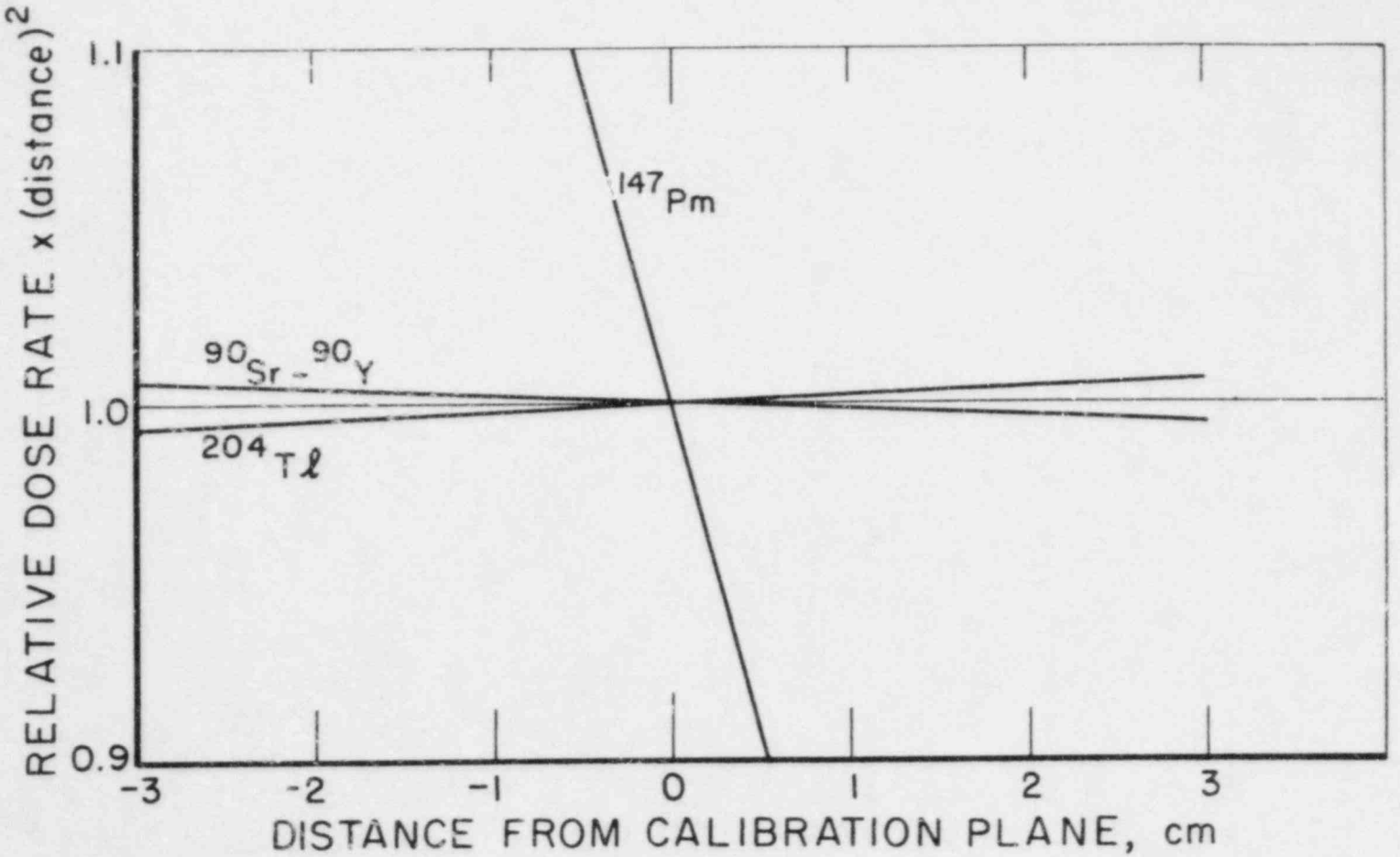


Figure B-13 Dependence of Dose Rate on Detector Positioning.

1.2.2 Gaseous Beta Emitters

An exposure chamber was designed and built in which radiation-protection instruments may be subjected to gaseous sources of beta radiation. The chamber also can be used to study radon exhalation and transport through materials of interest. The chamber is in the form of a right circular cylinder, three feet in diameter and three feet high. It is self-supporting, with stainless steel walls thick enough to allow for over-or-under pressurization by 10 percent of one atmosphere. Major access is through a clear plastic hood on top, with provision for five probe-access ports on the side, at various levels. Figure B-14 shows the partly constructed chamber prior to the installation of: the hood, with glove port and instrument shelf; a mass-flow detection instrument; circulating pumps, valves, piping, etc.; and a fan, placed at one-third of the height of the chamber, with the air flow directed tangentially upward.

Ampoules of radioactive gases of known nominal activities are introduced into the chamber through the top, and are then broken while the fan is running. This aids in distributing their contents uniformly throughout the air in the chamber. In order to determine exact radioactivity concentrations in the resulting gaseous medium, gas samples are taken by means of suction bulbs and counted. Concentrations then may be computed from the total volume of the chamber assembly of 0.846_2 m^3 (main tank: 0.6004 m^3; upper neck: 0.0579 m^3; mid-plane 2-inch neck: 0.0006 m^3; immersion hood: 0.1663 m^3; and side arm: 0.0210 m^3). Estimates of the attenuation of beta particles emitted by ^{133}Xe gas introduced into the air of the chamber showed that the chamber provides for a gaseous medium that is a good approximation of a semi-infinite beta emitter for an instrument placed at the top center or at the bottom center of the chamber.

1.3 Essentially Monoenergetic Electron Beams

Because of the strong dependence of instrument response on beta-particle spectrum, it is of advantage to perform some instrument response studies with essentially monoenergetic electrons, and thus to establish an instrument-response function. For this reason, the NBS 500-kV linear accelerator and the 4-MV electron Van de Graaff were adapted to this work by attaching to the beam-handling system a device capable of scanning the electron beam in two dimensions over an area large enough to cover a radiation-survey instrument with a sufficient degree of uniformity. After passing the scanning assembly, the beam was allowed to exit from the vacuum through a 16-cm^2 window, consisting of 25 μm of Kapton (cross-linked Mylar).

Beam Diagnostics

Studies were performed on the energy degradation of the stationary beam as a function of distance traveled in air and in the Kapton window, using an intrinsic germanium detector. Figure B-15 shows a representative plot of spectral end points, deduced from the pulse-height distributions in this detector, as a function of the traversed layer of air for a nominal 300-keV electron beam, prior to correction for the ~50-keV beam degradation in the Kapton window and in the window and deadlayer of the detector. The diameter of the portion of the beam cross sections over which beam intensity lies within ten percent of maximum was determined for the scanned electron beams at the source-to-detector distances for which the dose rates were suitable for the study of radiation-protection instruments. The results are shown in Table B-6, confirming that the beam cross sections are adequate for most instrument studies.

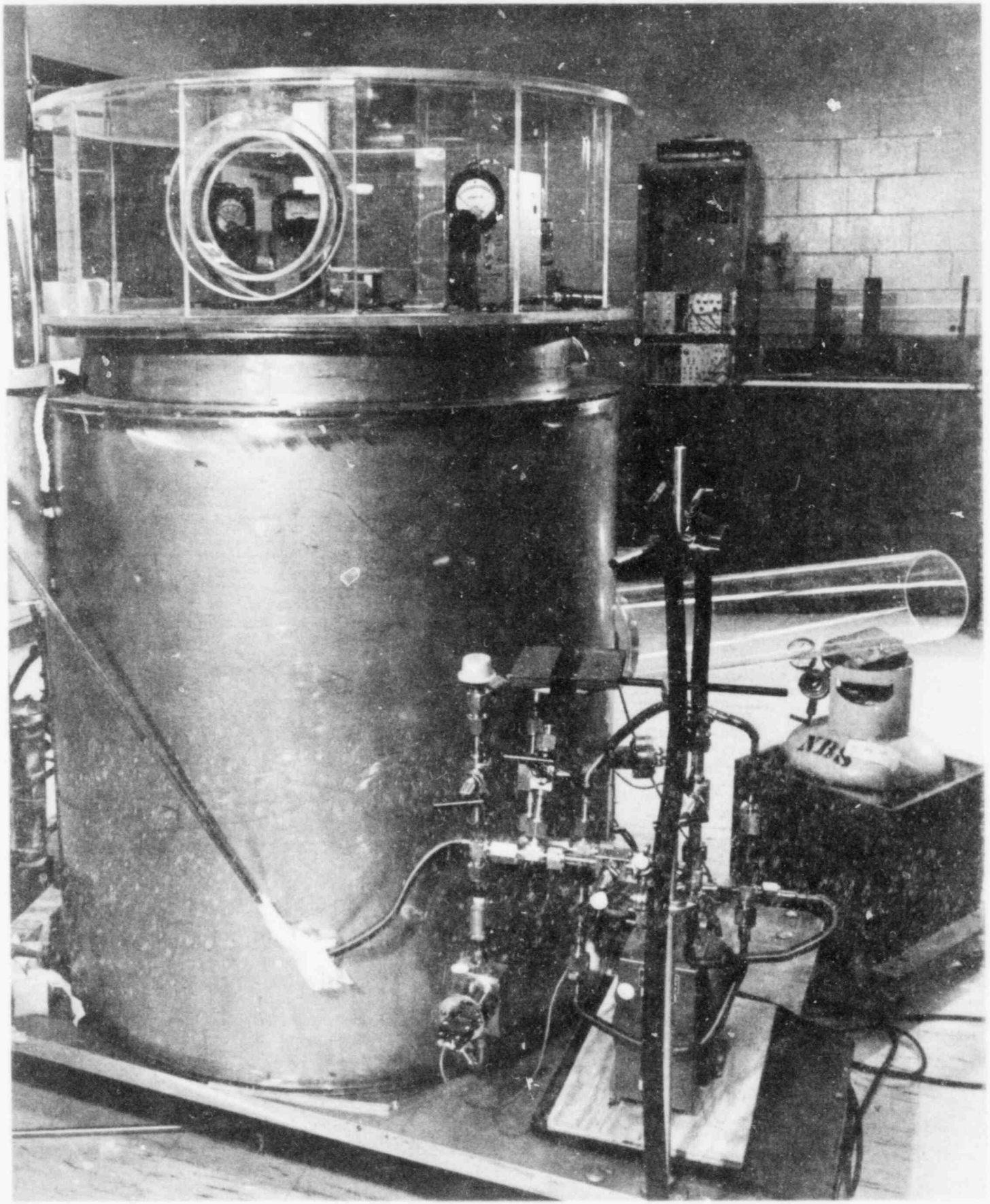


Figure B-14 Chamber for exposure of portable survey instruments to gaseous sources of beta radiation.

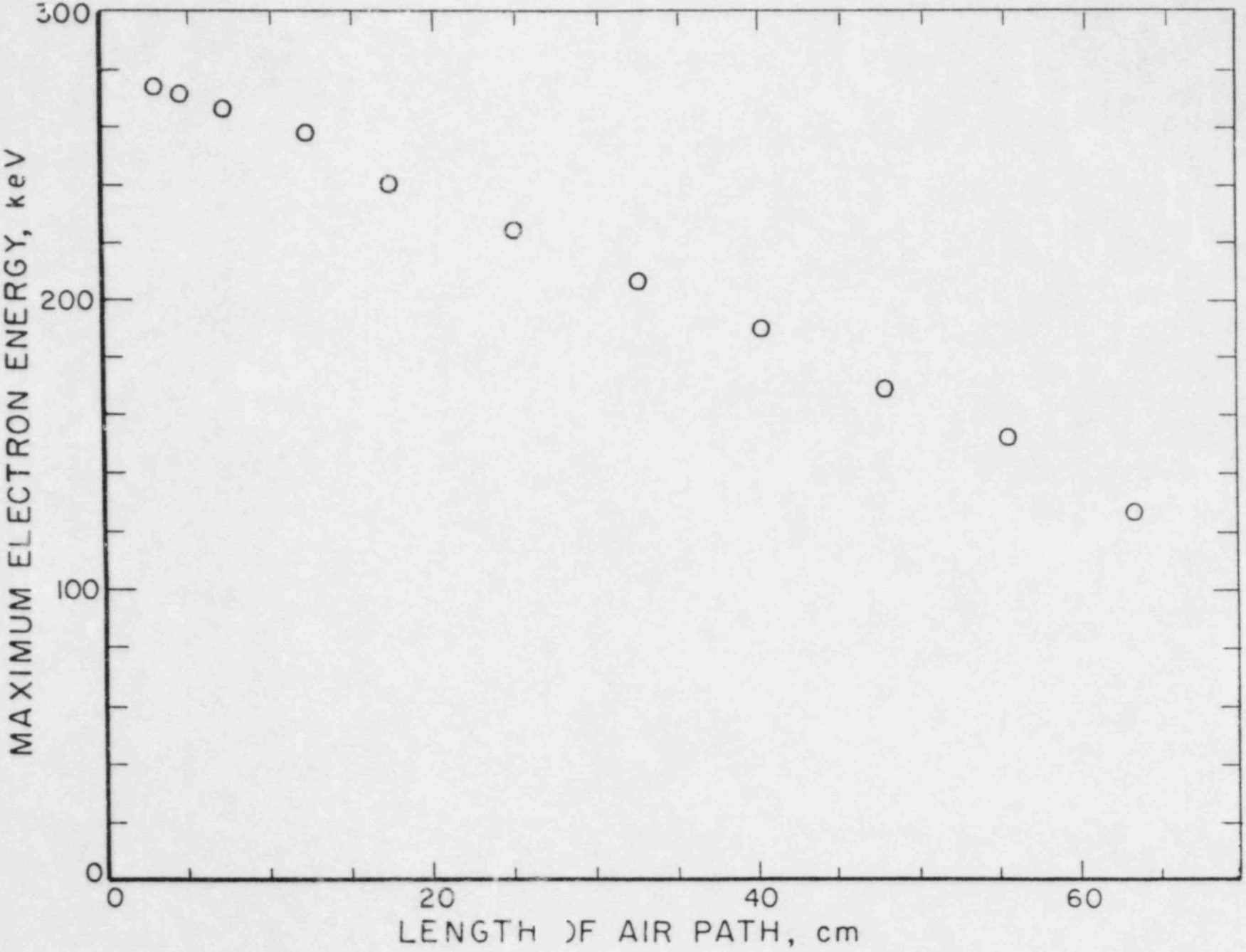


Figure B-15 Maximum Electron Energy as a Function of Length of Air Path.

Table B-6. Diameter of Portion of Beam Cross Section Over Which Intensity is Within 10 Percent of Maximum

Electron Energy	Diameter (cm)	
	for window-to-detector distance of:	
	20 cm	30 cm
200 keV	8.3	----
300 keV	6.7	11
400 keV	5.7	8.7
	50 cm	100 cm
1.5 MeV	8.9	22
2.5 MeV	5.7	14
3.5 MeV	4.4	11

Beam Dosimetry

Absorbed-dose rates to air were determined for electrons emerging from the vacuum with energies that were between 100 and 400 keV. The measurements were made at a location suitable for the study of radiation-protection instruments. The readings of the extrapolation chamber were compared with those of a large ionization chamber that was used as a beam monitor at a fixed location at the beam periphery, to permit correlation of absorbed-dose rates to instrument readings. This procedure can be used over the entire range of electron energies of interest, and is estimated to be capable of yielding values of absorbed-dose rates to water at the depths of interest, with uncertainties having an upper bound of around ten percent.

2. Studies of Instrument Response

2.1 Instruments Studied

Table B-7 gives a list of the types of survey instruments studied, of the types of detectors they incorporate, and of the minimum thickness of the detector "windows". Photographs of these instruments are shown in Figures B-16 through B-21. A more detailed description of their features follows.

The XETEX Model 305B Digital Exposure Rate Meter

This instrument uses two GM tubes to detect radiation. It is powered by four Type AA batteries and was supplied with a plug and charging unit for use if rechargeable (NiCd) batteries are used. The instrument has a three-digit readout which is cycled over the instrument counting-time base, at the end of which time a static display of the computed exposure rate is presented. Discrete LED indicators in the upper and lower right-hand corners of the readout indicate whether the measurement is in mR/h or R/h. The range change is automatic, exposure rates up to 100 mR/h being measured by the low-range GM tube while higher exposure rates are measured by the smaller, high-range, tube. The maximum reading is 99.9 R/h. Exposure rates above 100 R/h cause this instrument to cycle continuously.

The Ludlum Measurements Inc. Model 16 Analyzer

This instrument was purchased with a PR-0016 scintillation-detector probe. It has a fast-slow time-constant switch and a discriminator-window switch. Full scale reading is 500 counts per minute, with switch multipliers of x1, x10, x100, and x1000. No information is provided for conversion of count rate to exposure units. Instructions for setting high voltage, threshold level, and window width are provided. The counter can be used with proportional, GM, or scintillation detectors and is set to count correctly using a pulser. Calibration of the counter-detector system is accomplished by using a known radiation source to determine the probe "efficiency".

The Eberline Ion Chamber Survey Meter Model RO-2A

This is an ionization-chamber instrument with four exposure-rate ranges, 50 and 5 R/h, and 500 and 50 mR/h. The ionization chamber is located in the front of the bottom of the instrument, and has a thin window for beta-particle measurements. A protective window and sliding beta shield are at the bottom of the instrument case. The ionization chamber is polarized using two 9-volt batteries. There is some indication of lack of saturation at exposure rates greater than about 1 R/h.

The Eberline Geiger Counter Model E-520.

This instrument utilizes two GM tubes as detectors. The small internal GM tube is used for the x100 range only, full-scale reading for this condition being 2 R/h. The larger external GM tube operates when the range switch is in the x0.01, x0.1, x1.0, and x10 positions. Both GM tubes are shielded in an effort to minimize energy dependence for exposure measurements.

Table B-7. Types of Survey Instruments Evaluated

Name and Designation	Detector Incorporated	Minimum Thickness of Detector Window (mg/cm^2)
Xetex Digital Exposure Ratemeter, Model 305B	G. M. counter	30
Ludlum Model 16 Analyzer, with PR-0016 probe	NaI(Tl) crystal	1300
Eberline Ion Chamber Survey Meter, Model RO-2A	Ionization chamber	7
Eberline Geiger Counter, Model E-520, with the HP-270 external GM tube and Model SK-1 speaker	G. M. counter	30
Eberline Micro-R/h Meter, Model PRM-7	NaI(Tl) crystal	860
Eberline Teletector, Model 6112B	G. M. counter	90

Figure B-16

XETEX Digital Exposure Ratemeter

Model 305B

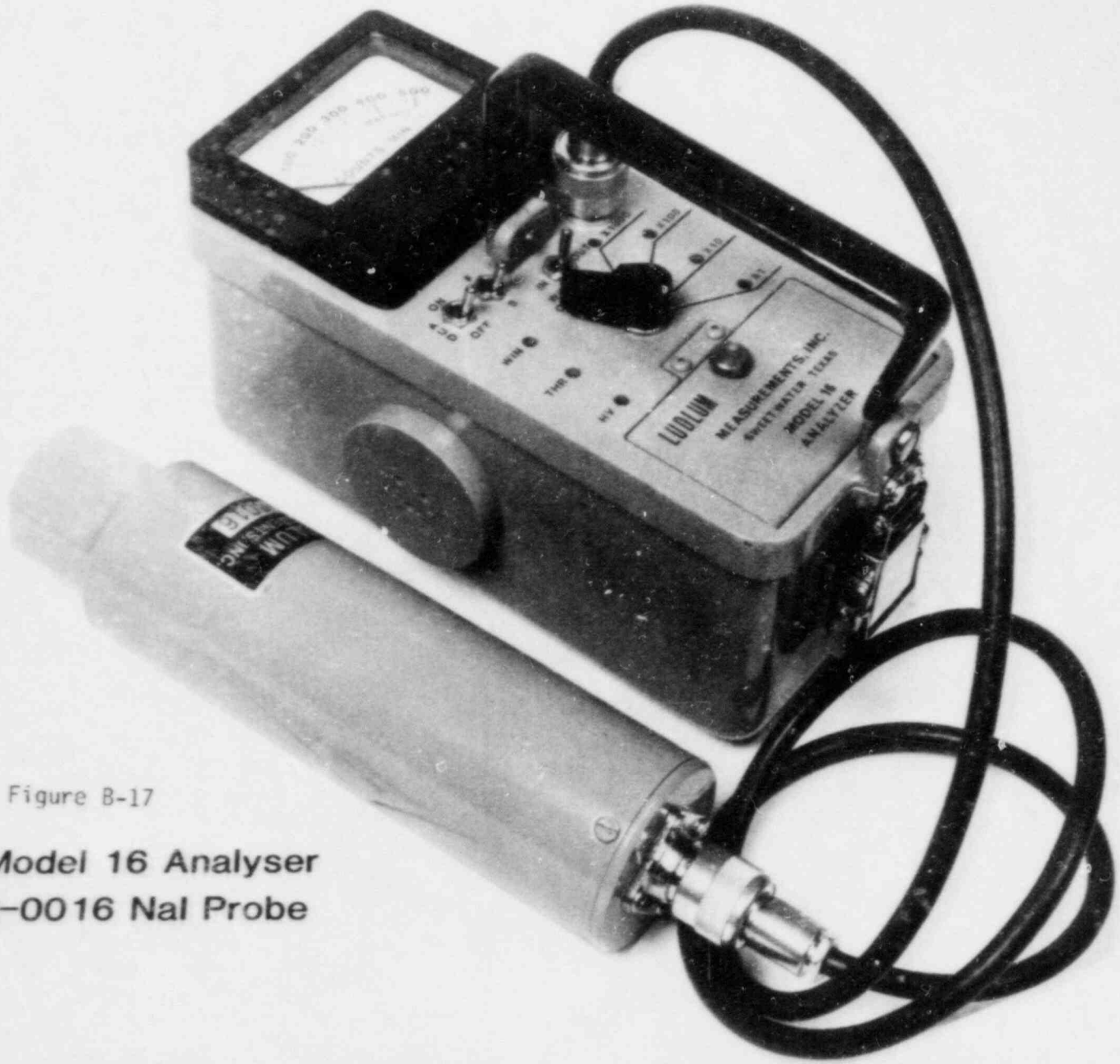


Figure B-17

Ludlum Model 16 Analyser with PR-0016 NaI Probe

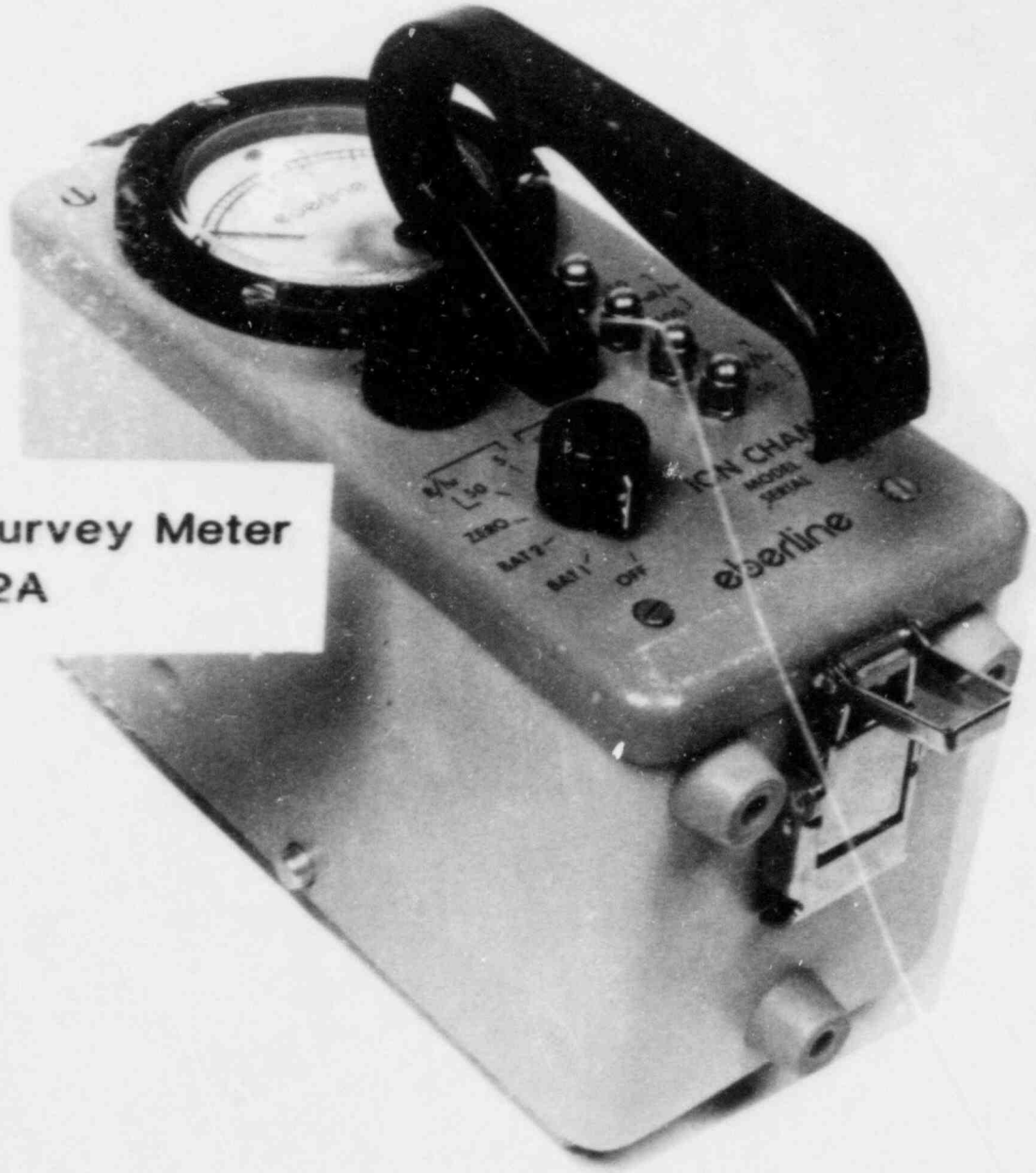


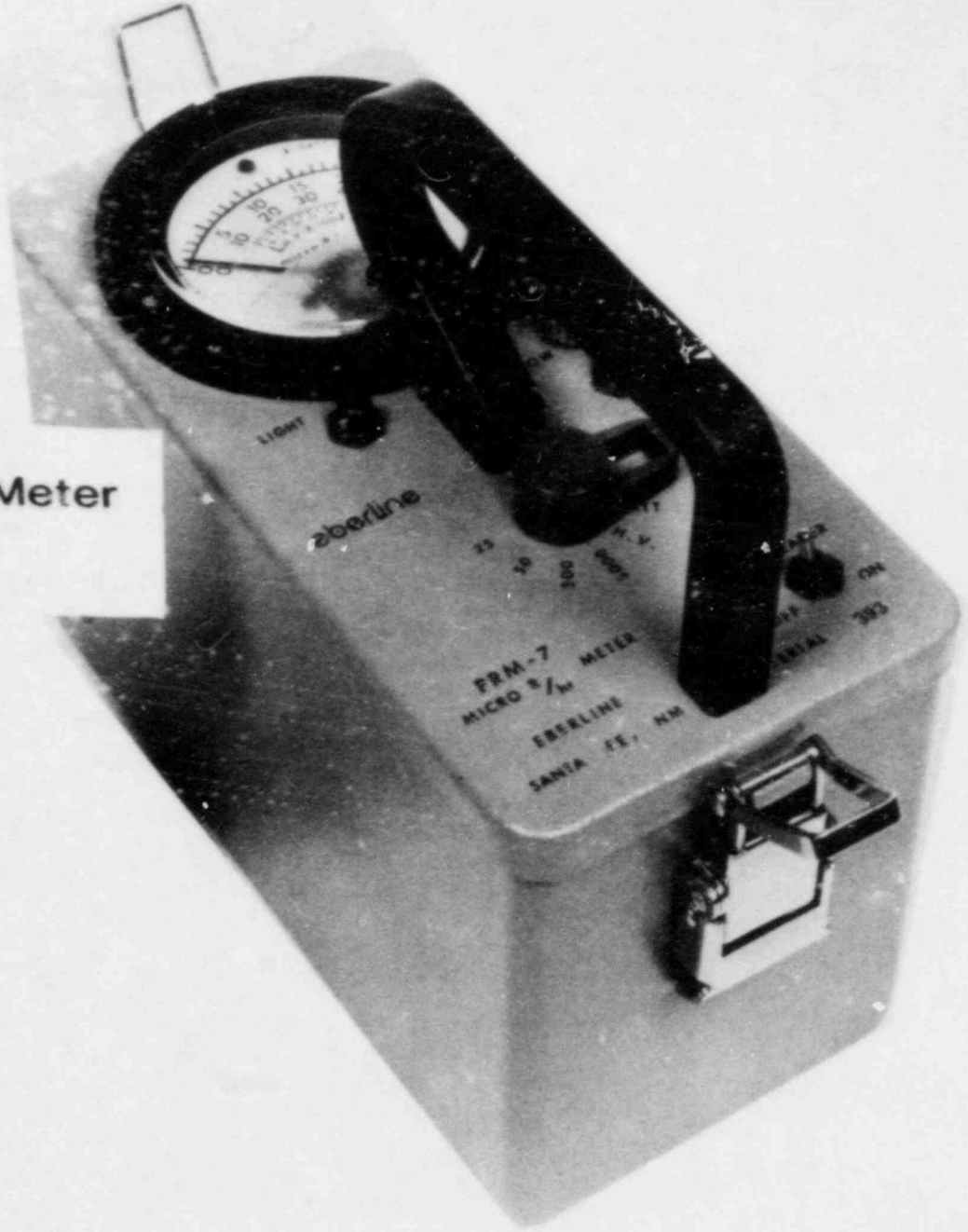
Figure B-18

Eberline Ion Chamber Survey Meter
Model RO-2A

Figure B-19 **Eberline Geiger Counter, Model E-520 with HP-270 external GM tube**

Figure B-20

Eberline Micro-R Meter
Model PRM-7



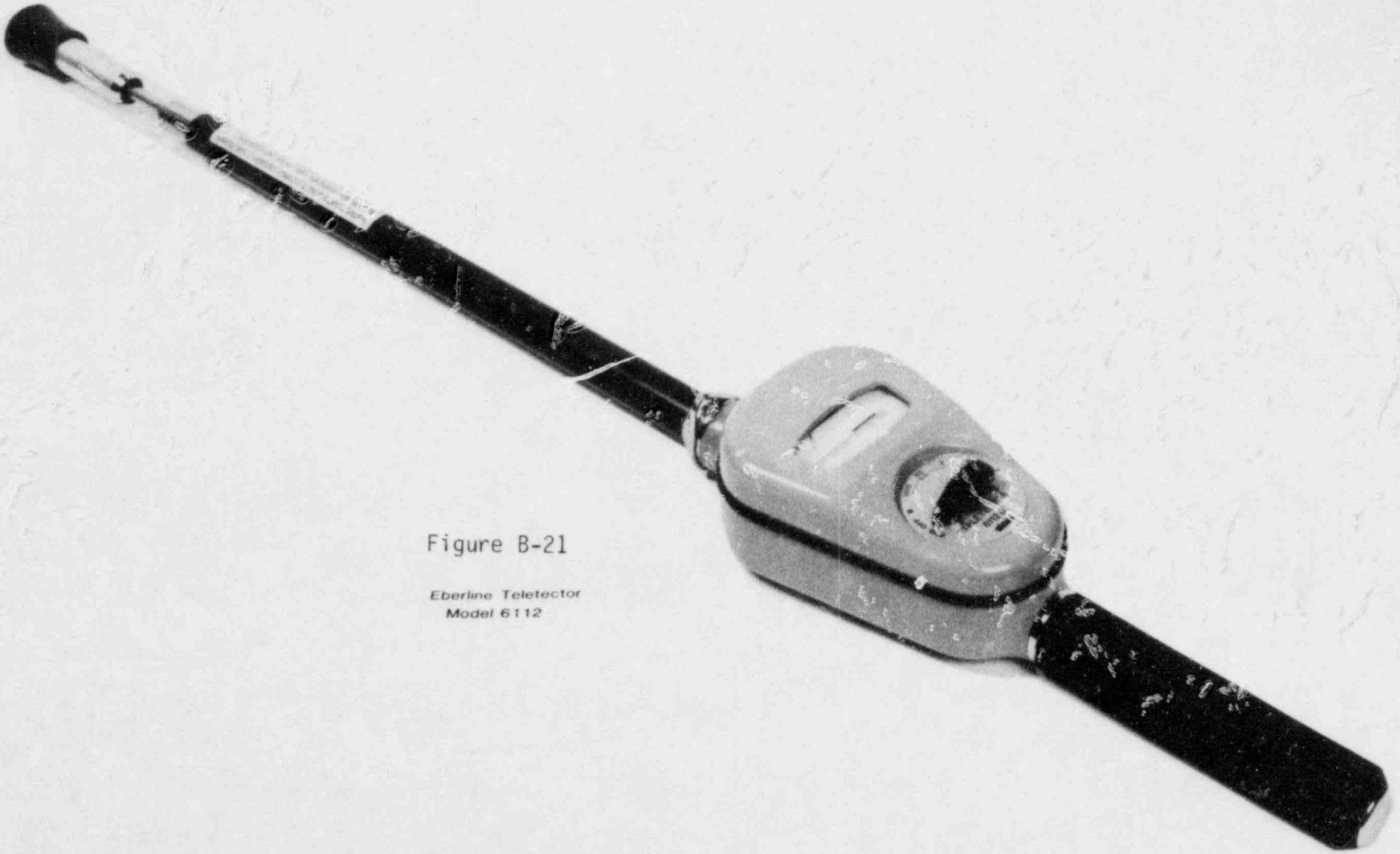


Figure B-21

Eberline Teletector
Model 6112

The Eberline Micro-R/h Meter Model PRM-7.

The instrument uses a scintillation detector to sense photon radiation. The most insensitive range is 5 mR/h full scale. Other r nges are 500, 50, and 25 μR/h, full scale.

The Eberline Teletector Model 6112B.

The instrument features a telescoping arm at the end of which is the detector assembly. With the arm fully extended the detectors are about 3.8 m (12 ft) from the readout, allowing measurements of radiation in inaccessible areas or from behind barriers. The instrument weighs about 3 kg (7 lb) and a shoulder strap is provided to assist in carrying it.

The detector assembly consists of two GM tubes, one for high-range measurements (1000 R/h and 50 R/h) and one for low-range measurements (2 R/h, 50 mR/h and 2 mR/h). The low-range GM tube has an end window for beta-ray detection with the window protected by a coarse screen and a removable rubber cap. The high-range GM tube is located on a circuit board about 7 mm off axis and behind the low-range GM tube (toward the readout). Both GM tubes are surrounded by a lead shield which is affixed to a fiber-board cylinder. The lead shield is about 0.2 mm thick around the low-range tube and about 0.8 mm thick around the high-range tube.

2.2 Study Conditions

Instrument response was determined for all types of radiation covered without any changes in "sensitivity" settings, which were maintained at factory levels. Since only one instrument of each type was available, no information could be obtained on variations in the performance of individual instruments of the same type.

The instruments were studied (1) in the photon beams over an energy range from ~40 keV to ~6.5 MeV; (2) in the beta-particle beams from ^{147}Pm, ^{204}Tl, and $^{90}Sr/^{90}Y$ sources (maximum energies between ~200 keV and ~2 MeV); (3) immersed in the ^{133}Xe gaseous beta-particle emitter; and (4) where considered useful, also in the close-to-monoenergetic electron beams of energies between 100 and 400 keV.

2.3 Response to Photon Beams up to 1250 keV

2.3.1 The XETEX Model 305B Digital Exposure Rate Meter

The linearity of the instrument response was tested for several exposure rates using gamma radiation. In addition, the dependence of the instrument response to various x-ray spectra was investigated. The results of these tests are shown in Table B-8, where the higher radiation energies are the gamma rays from ^{60}Co and ^{137}Cs, and the remaining energies are effective energies derived from absorption data for heavily filtered x rays.[7]

Table B-8. Study of Energy Dependence and Scale Linearity, XETEX Model 305B, SN 8284
(Radiation incident upon back of instrument.)

Radiation Energy (keV)	High-Range GM Tube		Low-Range GM Tube	
	Exposure Rate (R/h)	Sensitivity*	Exposure Rate (mR/h)	Sensitivity*
1250	30	1.05		
	3.5	1.08		
	1.0	1.10		
	0.40	1.08		
662	80	0.94	101	0.96
	8.0	0.98	4.9	1.09
	1.0	1.04	0.8	1.11
210	1.62	1.64	125	0.73
	0.48	1.64		
167	1.22	2.00	99	0.86
	0.42	2.04		
117	0.37	2.27	81	0.92
70	0.67	1.24	189	0.42
38			1527	0.005

*Sensitivity is defined here and in all subsequent tables in Part 3 as the quotient of the instrument reading and exposure rate.

The energy dependence of the response of the high-range GM tube is different from that of the low-range GM tube. The energy-compensating filter wrapped around the low-range tube is under a circuit board and cannot be seen directly; however, radiographs indicate it is also wrapped in a filter.

2.3.2 The Ludlum Measurements Inc. Model 16 Analyzer

The Analyzer was tested for its response to ^{137}Cs gamma rays and for heavily-filtered x-ray spectra. The slow time constant was used and the window was switched to "out". In all cases the radiation beam was directed perpendicular to the axis of the probe. The results are given in Table B-9. The sensitivity of this instrument is seen to be very dependent on the energy of the radiation. For example, the sensitivity for photons of 70 keV effective energy is eighteen times higher than it is for ^{137}Cs gamma rays.

The data shown are for the analyzer switches in the "window-out" position. The instrument in this case is a count-rate meter. With this switch in the "window-in" position, the analyzer can be set to discriminate against pulse heights greater than a selected level. No attempt was made to adjust high voltage, threshold, or window settings for measurements at the various energies. Readings with the window "in" for ^{137}Cs gamma radiation were found to be from 12 percent to 19 percent of the window "out" reading, depending on the radiation-scattering conditions. The corresponding sensitivities for these conditions would be factors of about 10 to 5 times lower than the sensitivities for the window "out" condition.

2.3.3 The Eberline Ion Chamber Survey Meter Model RO-2A

The instrument, when received, did not check properly for the BAT 2 condition and was returned to the company for repair. Upon its return, tests were performed at a few points for scale linearity and for energy dependence using the 500 mR/h range. The results are shown in Table B-10. In all cases, the radiation was directed toward the bottom of the instrument, with the beta shield closed. Since the energy dependence tests were carried out for about the same exposure rates, the results are not complicated by the instrument's rate dependence.

2.3.4 The Eberline Geiger Counter Model E-520

No tests were attempted for the x0.01 range, but some scale linearity checks were made on all the other ranges. Energy dependence was determined for both the internal and external GM tubes.

Table B-11 shows the results. The instrument is seen to exhibit some non-linearity for the higher exposure rates on the x10 and x100 ranges. This non-linearity does not influence the energy dependence data since the exposure rates were adjusted to make the instrument readings nearly the same at each energy.

Table B-9. Study of Energy Dependence and Scale Linearity, Ludlum Analyzer Model 16 with Scintillator Probe PR-0016 (All readings on the x1000 range.)

Radiation Energy (keV)	Exposure Rate (mR/h)	Reading (10^3 counts/min)	Sensitivity (10^6 counts/mR)
662	2.8	365	7.9
662	1.4	190	8.2
662	0.73	110	9.0
210	0.51	414	49
167	0.33	384	70
117	0.20	374	110
70	0.19	460	148
38	0.52	440	51

Table 3-10. Study of Energy Dependence and Scale Linearity, Eberline Ion Chamber Survey Meter, Model RO-2A, SN 953 (Readings corrected to 22°C and 760 mm Hg.)

Radiation Energy (keV)	Exposure Rate (R/h)	Sensitivity in Range			
		50 mR/h	500 mR/h	5 R/h	50 R/h
1250	10				1.02
	4.0			0.93	
	1.0			0.96	
	0.40		0.97		
662	40				0.89
	10				1.04
	4.0			0.93	
	1.0			0.96	
	0.36		0.97		
	0.10		0.99		
	(mR/h)				
	18	1.03			
	9.9	1.03			
210	380		1.06		
167	390		1.09		
117	340		1.15		
70	330		1.13		
38	430		0.93		

Table B-11. Study of Energy Dependence and Scale Linearity, Eberline Geiger Counter Model E-520, SN 2101
(Radiation incident normal to the bottom of the case.)

Radiation Energy (keV)	Range	Exposure Rate	Sensitivity*
		Internal GM Tube	
		(R/h)	
1250	x100	1.50	1.18
		0.50	1.25
662		1.79	0.97
		1.50	0.96
		0.89	1.01
210		1.62	1.11
167		1.32	1.33
117		1.21	1.47
70		2.48	0.76
38		1.53	0.06
		External GM Tube; beta-shield closed.	
		(mR/h)	
662	x0.1	1.9	0.97
		0.7	0.99
	x1	17	0.87
		14	0.88
		5	0.89
	x10	196	0.97
		153	1.02
		95	1.15
210		155	0.99
167		127	1.20
117		98	1.39
70		116	1.32
38		245	0.64

*Meter needle hangs up at 3/4 of full scale. Requires tapping for correct reading.

2.3.5 The Eberline Micro-R/h Meter Model PRM-7

Initial tests at NBS with collimated ^{137}Cs gamma-ray beams resulted in significantly lower sensitivities (lower by 25 and 40%, respectively, for two instrument ranges) than those given by the manufacturer, who calibrated using a small 4-π ^{137}Cs gamma-ray source with a calibration traceable to NBS. In order to demonstrate the reason for this discrepancy and the associated difficulties in the use of this type of instrument, studies were performed both with the collimated beams used for the other instruments, and with a ^{137}Cs gamma-ray source in a 4-π geometry, similar to that used by the manufacturer.

(a) Studies in collimated beams.

Table B-12 shows the results of the study of the energy dependence of instrument sensitivity for the 5000 R/h range. For ease of comparing the results of the measurements (columns 3 and 5) with the data of column 4, sensitivity is shown relative to that for ^{137}Cs gamma radiation, with the normalization factor given in a footnote. The sensitivity at 70 keV is seen to be sixteen times that for ^{137}Cs gamma radiation. This large energy dependence of the sensitivity is not unexpected. In fact, a comparison of the measured relative sensitivities with the ratio of the energy-absorption coefficients of NaI and air (column 4) shows that the measured values of sensitivity vary generally in accord with the expected sensitivities, except that, at low energies, measured sensitivity is modified by attenuation in the instrument case, the detector can, and the NaI(Tl) detector itself.

Table B-12. Study of Energy Dependence,
Eberline Model PRM-7 Micro-R/h Meter, Ser. No. 393
(Radiation incident normal to the bottom of the instrument.)

Radiation Energy (keV)	Range (μR/h)	Relative Sensitivity		
		Initially Measured[1]	Calculated[2]	Measured with Added Filtration[3]
1250	5000	0.43	0.78	0.45
662	"	1.00	1.00	1.00
210	"	5.5	5.9	4.4
167	"	7.4	10	5.4
117	"	11	28	5.5
70	"	16	95	2.1
38	"	10	39	0.20

[1]Sensitivity normalized at 662 keV (^{137}Cs gamma rays). Multiply by 0.76 to get absolute sensitivity.

[2]Ratio of NaI energy-absorption coefficient to that of air, normalized at 662 keV.

[3]1.3 mm Sn filter wrapped around detector; sensitivity normalized at 662 keV. Multiply by 0.71 to get absolute sensitivity.

(b) Studies in 4-π geometry.

Since the manufacturer uses a small calibrated ^{137}Cs gamma-ray source in a 4-π geometry to obtain the calibration associated with this type of instrument, studies were performed at NBS in a 4-π geometry as well as with collimated sources. The manufacturer provided the dimensions of the room used for calibration, and the source-to-instrument distances employed. The room available at NBS for studies in a 4-π geometry has solid concrete walls and is 9m x 6m x 4.5m high. A supporting stand, mounted on a track perpendicular to the long axis of the room, was used to support the instrument and source holders at a height of 2 m from the floor. The source-instrument axis was parallel to the long axis of the room. Maintaining the height above the floor and a source-to-instrument distance of 1 m, instrument sensitivity was determined with the source-instrument assembly in the center of the room, and with the assembly moved to locations closer to the 9-m long wall. Table B-13 shows that instrument sensitivity is markedly increased as the assembly is moved toward the scattering concrete wall. The room-scatter contribution to exposure rate was determined independently as a function of distance from the same wall, and of source-to-point-of-measurement distance, by comparing the exposure rate measured with a relatively energy-independent air-equivalent ionization chamber with that computed for the same location from the source-calibration data. The scatter contributions obtained in this way are shown in Table B-14. For a geometry similar to that used by the manufacturer in the calibration of the instrument's 500 μR/h range, the room-scatter contribution is seen to be ~11 percent.

Table B-13. Variation of Eberline Model PRM-7 Sensitivity with Proximity to a Scattering Surface (Instrument-to-source axis parallel to a 9-m wall, and 2 m from floor. Distance between instrument and ^{137}Cs source: 1 m).

Distance to 9-m Wall (m)	Sensitivity Relative to that at Room Center
3.0	1.00
2.5	1.04
2.0	1.06
1.5	1.09
1.0	1.19
0.5	1.35
0.25	1.53

Table B-14. Influence of Irradiation Geometry on Measured Exposure Rates from Open-Air (4-π) ^{137}Cs Gamma-Ray Source

Source to Chamber Distance (m)	Distance to Floor (m)	Distance to 9-m Wall (m)	Increase in Exposure Rate (%)
1.15	2.0	3.0	2.3
"	"	0.91	4.8
"	"	0.25	11.0
"	1.1	3.0	3.4
"	"	0.91	6.0
"	"	0.25	13.5
1.816	"	3.0	6.7
" *	" *	0.91*	10.6

*This geometry is similar to the one used by the manufacturer for calibration of the 500 μR/h range.

Based on these results, and considering only single Compton scattering from concrete (producing ~400-keV scattered photons), one arrives at an increase in sensitivity indication by ~19 percent in the manufacturer's ^{137}Cs gamma-ray field as compared with the sensitivity in a clean ^{137}Cs gamma-ray beam. In effect, there will be an even larger sensitivity increase since there will be contributions from multiple scattering as well, producing even lower photon energies. As a consequence, it may be concluded that the discrepancy found in the initial NBS tests is plausible, since, because of the considerable amount of low-energy scatter in the manufacturer's radiation field, the manufacturer adjusted the sensitivity control of the instrument (i.e., turned down the sensitivity indication) by more than would have been necessary, had the radiation field been that of a clean ^{137}Cs gamma-ray source.

(c) Conclusions regarding field use of this type of instrument.

The Eberline Micro R/h Meter, Model PRM-7, is a very sensitive type of instrument, but because of the strong energy dependence of its sensitivity, its general usefulness is doubtful unless it is calibrated (and its sensitivity is adjusted) using a radiation field identical with the one to be measured. This means that, in many instances, the initial instrument calibration by the manufacturer may be useless or even misleading. (Note that, in the case of the NBS instrument, the manufacturer's sensitivity adjustment led to a material underestimation of exposure rate in the NBS collimated ^{137}Cs gamma-ray beam.)

The general usefulness of this instrument could be increased by decreasing the energy dependence of its sensitivity through added filtration around the detector. To demonstrate this, we surrounded the NaI(Tl) crystal with a 1.3-mm shield of tin (which is not necessarily the optimum choice), and then repeated our study of the sensitivity as a function of photon energy. The results are shown in the last column of Table B-12. The sensitivity peak in the range of 70 to 200 keV is seen to be reduced, while there is relatively little influence on the sensitivity for ^{137}Cs or ^{60}Co gamma radiation; yet, the sensitivity is suppressed excessively below 70 keV. However, by using suitable filter materials or combinations of materials, it should be possible to optimize the dependence of sensitivity on photon energy in the energy range of interest.

Another approach to circumventing the problem with survey instruments incorporating high-atomic-number detectors such as NaI(Tl) is taken in the Ludlum Analyzer, Model 16. Its detector, with the analyzer window "out", is influenced by scattered radiation from room surfaces in the same way as the Eberline Micro R/h Meter, Model PRM-7. But the Ludlum Analyzer scale is in units of count rate, with the responsibility for calibration in terms of other quantities left to the user.

2.3.6 The Eberline Teletector, Model 6112B

The instrument was tested using cesium-137 gamma rays and heavily filtered x rays. In tests for high-range exposure rates the position of the high-range tube was known and the 7 mm offset from the probe central axis was taken into account.

The instrument is powered by four "C" batteries. The condition of the battery supply is checked with the control switch in the "B" position. A black line over the upper third of the meter scale is the range for indication of battery condition. The battery condition was checked before all tests and found to be within the range defined by the black line. During the course of the tests, as the batteries became depleted, the battery test reading decreased until it no longer reached the black line on the meter. The effect of battery condition on the meter readings was found by using a precision power supply in place of the batteries. The effect of the battery condition on the instrument reading is shown in Table B-15, where it is shown that exposure rate readings on the high range decrease by 14 percent for a decrease from 6.0 volts to 4.0 volts (the minimum indicated by the black line). Since the actual battery potential available to the instrument during the various radiation measurements is not known, the relationship of readings taken at different times is also not known. As a result measurement data such as for energy dependence are normalized to measurements taken on the same day.

Initial testing of the Teletector was performed using collimated-beam cesium-137 gamma-ray sources. Three different sources were used to produce exposure rates extending from about 1 R/h to 670 R/h, allowing measurements on the 2, 50, and 1000 R/h ranges. The results of the measurements where the high-range GM tube is utilized are given in Table B-16 in terms of sensitivity. Sensitivity is defined here as the quotient of the instrument reading and the standard exposure rate. There appears to be a trend downward in sensitivity for the high-range GM tube as the exposure rate increases. There is some difficulty in estimating readings on the logarithmic scale if the readings are between scale divisions. The uncertainty in readings is reduced by positioning the detector in the gamma-ray beam so as to produce readings on scale divisions. This could not be done in all cases.

Table B-15. Change in Teletector Readings with Change in Power Supply Potential for Constant Exposure Rate (2 R/h Range)

Potential (volts)	Teletector Reading (R/h)	Teletector Readings Normalized to Reading at 6.0 volts
6.2	1.80	1.03
6.1	1.75	1.00
6.0	1.75	1.00
5.5	1.70	0.97
5.0	1.65	0.94
4.5	1.60	0.91
4.0	1.50	0.86
3.9	1.55	0.88
3.8	0.60	0.34

Table B-16. Sensitivities for Teletector Model 6112B High-Range GM Tube Using Cesium-137 Gamma Rays

Range (R/h)	Reading (R/h)	Exposure Rate (R/h)	Sensitivity (Old batteries)
1000	90	100	0.90
	130	150	0.87
	175	200	0.88
	260	300	0.87
	340	400	0.85
	420	500	0.84
	563	672	0.84
50	1.7	1.76	0.97
	3.0	3.34	0.90
	5.0	5.65	0.88
	7.0	7.94	0.88
	7.2	8.19	0.88
	10	11.8	0.86
	15	17.5	0.86
	20	22.5	0.89
	25	27.8	0.90
	30	33.4	0.90
	40	48.1	0.83
	50	65.2	0.77

Tests for sensitivity for the low-range tube were carried out using, in addition to the collimated beam source, small cesium-137 sources in a 4π geometry. The data are shown in Table B-17, where sensitivities are given for old and new battery complements. As opposed to the downward trend in sensitivity for the 50 R/h and 1000 R/h ranges as the exposure rate increases, the sensitivity for the 2 R/h range increases with increase in exposure rate. Within reading accuracy there appears to be no trend in sensitivity for the 2 mR/h and 50 mR/h ranges. The data of Tables B-16 and B-17 are reduced to mean sensitivities in Table B-18 for ease of comparison of sensitivities for the different ranges, as well as comparison of data for old and new battery complements.

Table B-17. Sensitivities for Teletector Model 6112B Low-Range GM Tube Using Cesium-137 Gamma Rays

Range (R/h)	Reading (R/h)	Exposure Rate (R/h)	Sensitivity (Old batteries)	Sensitivity (New batteries)
2	1.0	0.85	--	1.18
	1.0	0.99	1.01	--
	1.49	1.18	--	1.26
	1.5	1.42	1.06	--
	2.0	1.51	--	1.32
	2.0	1.78	1.12	--
(mR/h)	(mR/h)	(mR/h)		
50	1.6	1.59	--	1.01
	2.6	2.68	--	0.97
	3.5	3.45	1.01	--
	5.0	5.23	--	0.96
	8.5	8.44	--	1.01
	9.5	10.5	0.90	--
	15	15.5	--	0.97
	33	34.8	--	0.95
	34	40.2	0.85	--
	46	47.9	--	0.96
2	0.08	0.133	0.60	--
	0.10	0.137	0.73	--
	0.18	0.220	--	0.82
	0.45	0.563	--	0.80
	0.65	0.903	0.72	--
	0.90	1.14	--	0.79
	1.3	1.54	0.84	--
	1.7	2.17	--	0.78
	2.0	2.73	0.73	--

Table B-18. Mean Sensitivities for Teletector, High- and Low-Range GM Tubes

Range	Mean Sensitivity (Old batteries)	Mean Sensitivity (New batteries)
1000 R/h	0.86	--
50 R/h	0.89	--
2 R/h	1.09	1.25
50 mR/h	0.92	0.98
2 mR/h	0.72	0.80

The dependence of the Teletector exposure readings on the energy of the radiation was investigated for both high- and low-range GM tubes using heavily filtered x radiation. The combinations of x-ray tube potential and filtration are the NBS H series for which effective energies have been determined. The results of the measurements are shown in Table B-19, where the data are normalized to the sensitivities for the H300 combination of x-ray tube potential and beam filtration. The effect of the lead shield on the high-range GM tube response can be seen by the drop in sensitivity between 80 keV and 100 keV (the K shell critical x-ray absorption energy is about 88 keV). This effect is not obvious in the data for the low-range GM tube and the 2 R/h range; however, for the 50 mR/h range where additional copper filtration was used to lower the exposure rate and higher effective energies are produced, evidence of the lead absorption edge is seen in the sharp drop in sensitivity above 80 keV and the relatively flat response between 120 keV and 166 keV. These data are shown in Table B-20 where the x-ray effective energies are indicated as being greater than the H series effective energies but have not been determined.

Table B-19. Dependence of Teletector Model 6112B Exposure Rate Readings on Radiation Energy

NBS Beam Code	Effective Energy (keV)	Normalized Sensitivities*	
		Low-Range GM Tube (2 R/h Range)	High-Range GM Tube (50 R/h Range)
H50	38	0.12	0.01
H60	46	0.59	0.02
H100	80	2.62	0.79
H150	120	1.78	0.56
H200	166	1.42	0.93
H250	211	1.17	1.04
H300	252	1.00	1.00

*The sensitivity, at H300, for the low-range GM tube is 0.91 and for the high-range GM tube it is 1.31.

Table B-20. Dependence of Teletector Model 6112B 50 mR/h Range Exposure Rate Readings on Radiation Energy

X-ray Tube Potential (kV)	Effective Energy (keV)	Normalized Sensitivity*
50	>38	0.12
60	>46	0.81
100	>80	2.35
150	>120	1.44
200	>166	1.36
250	>211	1.11
300	>252	1.00

*The sensitivity for an x-ray tube potential of 300 kV, the H300 filters, plus additional copper filtration, is 0.80.

2.4 Response to ~6.5-MeV Photon Beam

2.4.1 Procedure

Instrument sensitivity was determined with the geometric center of the instrument's radiation-sensitive volume (the "detector") at a distance of 1 m from the source. Layers of plastic were added over the front surface, in order to establish quasi-electron equilibrium and thus eliminate a possible influence on the instrument response of the electron and/or low-energy photon contamination in the beam.* Sensitivity was expressed as scale reading per unit of absorbed dose rate to water at a depth of 2.5 cm in a Lucite phantom, obtained from the readings of the calibrated NE 110 plastic scintillator which was used as beam monitor. In order to associate scale readings of the survey (rate) meters in the photon beam whose intensity fluctuated in time with the reading of the calibrated (integrating) beam monitor, scale reading per monitor count was obtained by averaging up to twenty or more individual scale readings taken during each of three successive thirty-second periods, and dividing their average by the value of the monitor counts integrated over the same periods.

*The measurements on the Eberline Model E-520 Geiger Counter were performed with its probe both behind Lucite slabs and enclosed in Lucite cylinders, with wall thicknesses of 2 and 5 cm, respectively. Within the experimental errors, the results were the same, confirming that complete enclosure in Lucite of the active detector volume was unnecessary.

To check on the constancy of the scintillation monitor, its readings were compared with those of an Exradin, Model A6, 800-cm^3 ionization chamber with an added cubical Lucite shell of a thickness of 2.5 cm. Based on a total of close to 50 thirty-second runs, the relative coefficient of variation for the ratios of the readings of the scintillation and ionization monitors was found to be ±1.6 percent, with most of the uncertainty probably stemming from leakage of the ionization chamber. Therefore, the use of the scintillation monitor for establishing the relationship to absorbed-dose rate as determined from the readings of the LiF TLD-100 dosimeters was considered adequate.

2.4.2 Results

Instrument sensitivity (scale reading per unit absorbed-dose rate to water at a 2.5-cm depth in a Lucite phantom) was determined as a function of Lucite thickness added over the detector. Figure B-22 shows semilogarithmic plots of the results. For added Lucite thicknesses of less than ~2 cm, the shape of the curves of sensitivity-versus-Lucite thickness is seen to vary considerably with instrument type, depending mainly on wall thickness of the detector. For larger thicknesses of added Lucite, the curves reflect, at least qualitatively, the decrease in instrument response due to beam attenuation in Lucite. The sensitivity values shown in the figure for an added 2.5 cm of Lucite were computed from the least-squares fit to the data for added Lucite thicknesses of more than ~2 cm.

The results are summarized in Table B-21, giving the sensitivity of the instruments irradiated with the detector behind 2.5 cm of Lucite, with absorbed-dose rate to water determined at a depth of 2.5 cm in the Lucite phantom. Listed are nominal dose rates for the calibration of each instrument, sensitivity and its units, and instrument orientation during calibration. Here, "vertical" means that the plane of the meter dial was perpendicular to the incident photon beam, and "horizontal, side" means that the dial plane was parallel to the beam, with the instrument case on its side.

In the fourth column of Table B-21, sensitivity in the ~6.5-MeV beam is compared with that to ^{137}Cs gamma radiation (ignoring the relatively very minor correction arising from the ^{137}Cs gamma-ray beam having been characterized in terms of exposure rate and the ~6.5-MeV beam in terms of absorbed-dose rate to water). The Teletector, Model 6112B, demonstrates sensitivity in the higher-energy beam that is essentially the same as for ^{137}Cs gamma radiation. Without any further adjustment, the sensitivity of the Eberline Ion Chamber Survey Meter, Model RO-2A, is seen to come to within 20 percent of that for ^{137}Cs gamma radiation, and the sensitivity of the Xetex Digital Exposure-Rate Meter, Model 305B, comes to within a factor of two--both in the "safe" direction (i.e., reading high). The two instruments incorporating NaI(Tl) detectors read low in the ~6.5-MeV beam by factors of 2.5 to 3.3 unless their sensitivity is adjusted for the particular radiation field.

2.4.3 Recommendation

If any of the instruments is to be employed for surveys in an area in which photons of energies in the vicinity of 6 MeV may be present, it is suggested that readings be taken behind increasing thicknesses of plastic over the front of the instrument, in order to establish an attenuation curve in plastic for

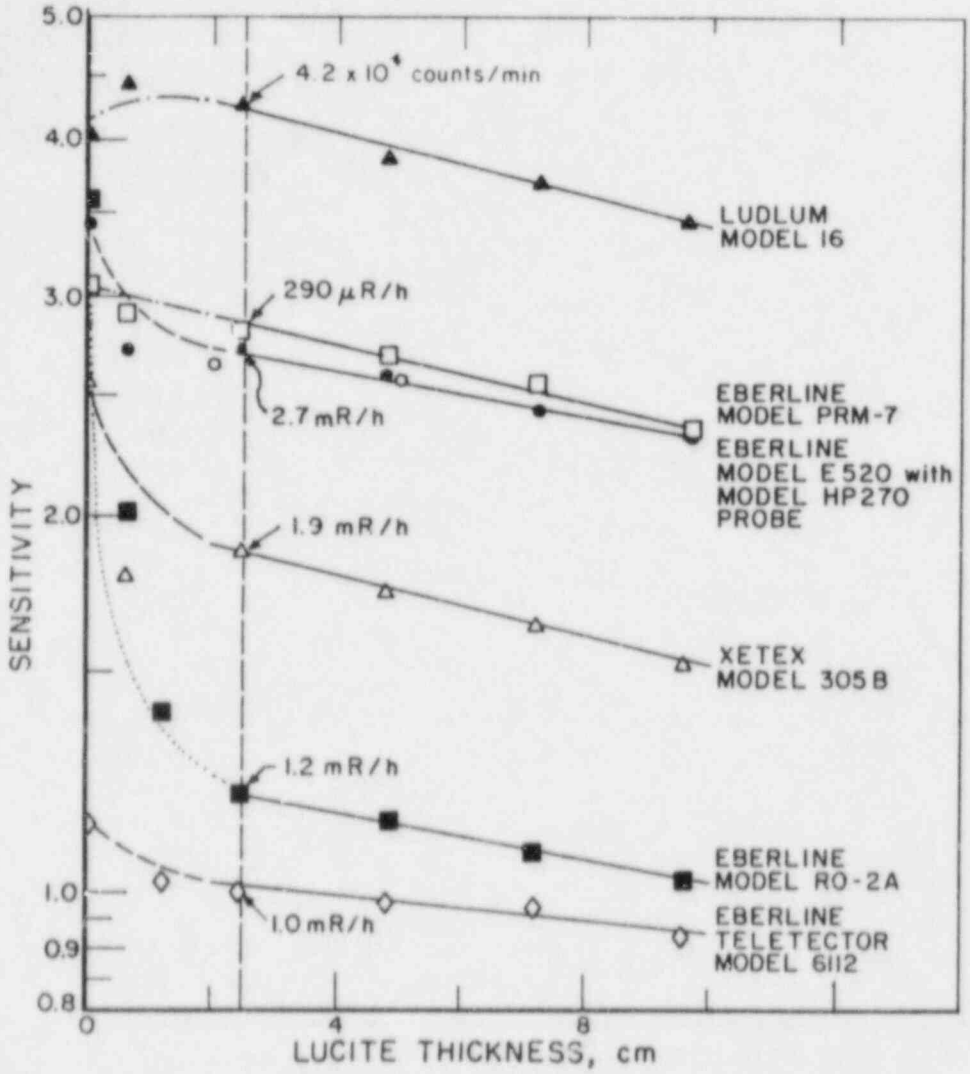


Figure B-22 Instrument Sensitivity (Scale Reading per Absorbed-Dose Rate to Water at a 2.5-cm Depth in a Lucite Phantom) as a Function of Lucite Thickness Added Over the Front Surface of the Active Detector Volume. Solid straight lines: Least-squares fit to the data. The values for the sensitivities given at the arrows (for an added Lucite thickness of 2.5 cm) were computed from the least-squares fit. For the Eberline Geiger Counter, Model E-520, the full circles were obtained with the probe completely enclosed in Lucite cylinders of the respective thicknesses.

Table B-21. Instrument Sensitivity in the ~6.5-MeV Photon Beam at a Depth of 2.5 cm in Lucite

Instrument	Nominal Dose Rate (mrad/h)	Sensitivity		Meter Orientation
		Absolute	Relative to 662 keV Sensitivity	
Xetex Digital Exposure-Ratemeter, Model 305B	20	1.9 (mR/h)/(mrad/h)	~2.0	vertical
Ludlum Model 16 Analyzer	10	4.2×10^4 (counts/min)/(mrad/h)	~0.3	vertical
Eberline Ion Chamber Survey Meter, Model RO-2A	30	1.2 (mR/h)/(mrad/h)	~1.2	vertical
Eberline Geiger Counter, Model E520, with HP-270 External GM probe	30	2.7 (mR/h)/(mrad/h)	~2.3	vertical
Eberline Teletector, Model 6112B	25	1.0 (mR/h)/(mrad/h)	~1.2	horiz., side
Eberline Micro R/h meter, Model PRM-7	10	290 (μR/h)/(mrad/h)	~0.4	horiz., side

the radiation field to be surveyed. This is necessary because the components of the particular radiation field may be different from those encountered in the $^{19}F(p,\alpha\gamma)^{16}O$ beam employed by NBS for response studies. This attenuation curve for the field to be surveyed then may be used for estimating the dose equivalents at the depths of interest.

2.4.4 Estimate of Overall Uncertainty of Results

Among the individual components that enter into an estimate of the overall uncertainty associated with the instrument sensitivities presented in this section are:

(a) Determination of absorbed-dose rate to water from TLD measurements in Lucite (see also Section 1.1.3), and calibration of the monitor in terms of this absorbed-dose rate.

(b) Positioning of instruments such that the geometric center of the detector is at the point of known absorbed-dose rate.

(c) Least-squares fit of instrument sensitivity data obtained as a function of thickness of Lucite over the instrument's surface.

(d) Ability to read instrument scale and to relate average of scale readings (a rate) to monitor reading (an integral reading). This uncertainty varies with the type of instrument.

We estimate an upper bound for the overall uncertainty of between ±20 and ±25 percent. While this is a relatively large uncertainty, it probably is sufficient for obtaining the information required for the selection of the type of instrument best suited for surveys in ~6-MeV photon fields.

2.5 Response to Beta-Particle Beams

From a comparison of Table B-4, giving average and maximum ranges of the beta-particle sources available at NBS for these studies, and Table B-7, giving pertinent instrument characteristics, it is evident that some of the instruments are not equipped with sufficiently thin windows to give a response to the beta particles from all three types of available sources. Nevertheless, all six types of instruments were initially placed in the beams of all three types of sources. Measurements were made both with the geometric center of the sensitive detector volumes and with their "beta windows" at the distance for which absorbed-dose rate to tissue was known.

Table B-22 shows the results of the measurements made with the geometric center at the point of known absorbed-dose rate. The relationship between the results of these measurements and the measurements with the point of known absorbed-dose rate at the "beta window" is shown in Figure B-23 for the Eberline Model RO-2A instrument, demonstrating the importance of a detailed description of instrument-irradiation conditions. The fact that all instruments had to be studied at the same distance from a particular source in order to guarantee spectral comparability presented a difficulty since it made it impossible to select absorbed-dose rates providing mid-scale readings. As a consequence, instrument reading in some instances was off-scale on one range and close to

Table B-22. Instrument Sensitivity to Beta Particles, with Measurements Referred to Geometric Center of Sensitive Volume

Instrument	Absolute Sensitivity				Sensitivity Relative to ^{137}Cs Gamma Rays		
	Units[1]	$^{90}Sr/^{90}Y$	^{204}Tl	^{147}Pm	$^{90}Sr/^{90}Y$	^{204}Tl	^{147}Pm
XETEX Digital Exposure-Ratemeter Model 305B (6)	$\frac{mR/h}{mrad/h}$	0.00[2]	0.04	(3)(5)	0.00[2]	0.04	(3)(5)
Ludlum Model 16 Analyzer	$\frac{counts/min}{mrad/h}$	230[4]	86[4]	110[4][5]	(4)	(4)	(4)(5)
Eberline Ion Chamber Survey Meter, Model RO-2A	$\frac{mR/h}{mrad/h}$	0.90	0.44	0.14	0.93	0.43	0.14
Eberline Geiger Counter, Model E520, with HP-270 External GM probe	$\frac{counts/min}{mrad/h}$	680	36	(3)(5)	0.58[7]	0.03	(3)(5)
Eberline Teletector, Model 6112	$\frac{mR/h}{mrad/h}$	0.16	0.022	0.0009[5]	0.13	0.02	0.001
Eberline Micro R/h Meter, Model PRM-7[6]	$\frac{\mu R/h}{mrad/h}$	3.0	0.86[4]	2.6[5]	0.004	(4)	(4)(5)

(1) The units in the numerator are for scale reading, those in the denominator for absorbed-dose rate to air at the point of measurement.

(2) Dose rate too high for low-level G.M. tube, resulting in a "zero" reading, because, in the calibration geometry used, the high-level tube was shielded from the beta particles of the source.

(3) Observed reading close to background.

(4) Window thickness greater than CSDA range of beta particles from this source.

(5) Window thickness greater than effective range of ^{147}Pm beta particles as measured in Mylar with the Eberline Model RO-2A instrument.

(6) For these instruments, sensitivity values were obtained by subtracting from the measured values a background estimated from readings with the source shutter closed.

(7) CPM converted to mR/h using 1200 CPM ≈ 1 mR/h.

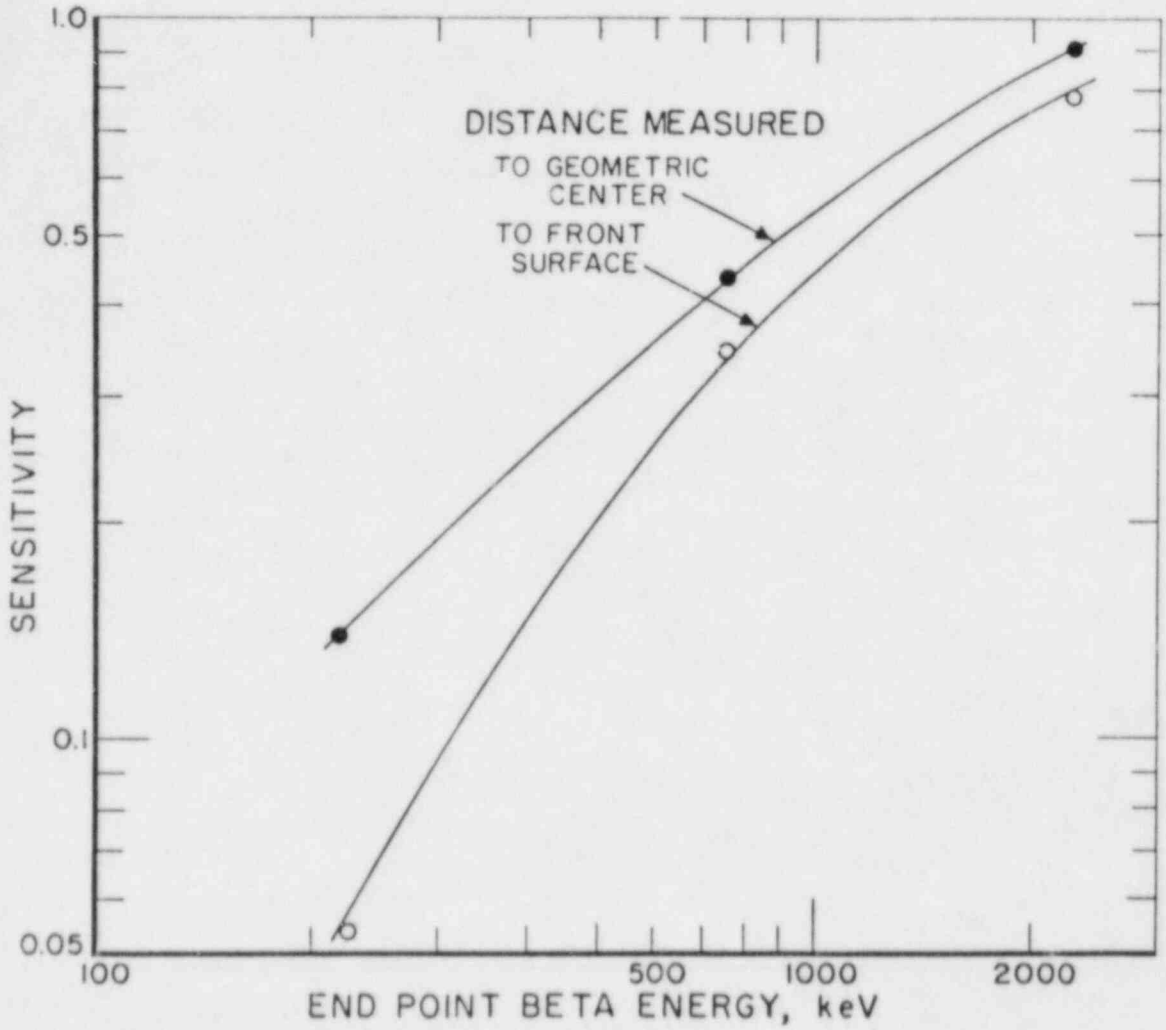


Figure B-23 Relationship Between Measurements Made with the Eberline Ion Chamber Survey Meter, Model RO-2A, with the Geometric Center and with the Front Surface of the Detector at the Point of Known Absorbed-Dose Rate.

the bottom of the scale on the next range. The most severe case occurred with the Xetex Model 503 instrument, which gave a reading of 0.00 mR/h when the low-level GM tube was facing the $^{90}Sr/^{90}Y$ source and the high-level tube was shielded by parts of the instrument.

Table B-22 shows that the Eberline Model RO-2A instrument, having the thinnest entrance window, is the only type studied that can be used over the entire beta-particle range covered, and, under the chosen irradiation conditions, has a sensitivity to ^{90}Y beta particles that is within 20 percent of its sensitivity to ^{137}Cs gamma-ray photons (see also Table B-10). Yet, for ^{147}Pm beta particles, its sensitivity is lower by a factor of ~7. Both NaI(Tl) detectors (Eberline Model PRM7 and Ludlum Model 16) detected significant amounts of radiation (probably bremsstrahlung and some photons) even with the source shutter closed. The behavior of response as a function of distance from the source suggested that some of this radiation originated in the vicinity of the source or source shutter. The effect was reduced significantly by a 1/4-inch steel plate in front of the detector.

2.6 Response to Monoenergetic Electron Beams

Inasmuch as the purpose of this study was to examine the response of the six types of instruments to electrons corresponding to beta particles lower in energy than those from ^{147}Pm, but none except the Eberline Model RO-2A instrument was previously found to have a sufficiently thin entrance window to admit such beta particles, this was the only instrument studied. Electron beams of energies 100 to 400 keV at their point of exit into air were employed. Table B-23 shows sensitivity data for this instrument, obtained at the indicated distances from the exit window of the electrons into air to the instrument's front entrance window of 7 mg/cm^2, where absorbed-dose rate to air had been determined. Since the upper bound on the uncertainty of these data is about ±50 percent, sensitivity is given with one significant figure only. The values shown seem grossly compatible with the instrument's sensitivity to ^{147}Pm beta particles shown in Table B-22.

2.7 Response to Gaseous Beta Emitter

The response of the survey instruments when immersed in a ^{133}Xe gas atmosphere was studied. The chamber used for these studies is described in Section 1.2. Five of the instruments were placed on a well-ventilated shelf inside the chamber's special plastic hood. Each instrument was within easy reach of a single glove port, and each instrument or its probe could be placed at the central measurement position, from which it was estimated to view a semi-infinite cloud of ^{133}Xe beta emissions. The sixth instrument, the Teletector, because of its length, was placed in a side arm attached to the chamber at the mid-plane. The GM-tube probe was inserted into the chamber a nominal 15 cm, which, it was estimated, also viewed a semi-infinite cloud of ^{133}Xe beta emission.

The experiment was conducted three times to achieve a range of ^{133}Xe concentrations inside the chamber, and corresponding dose rates to the chamber air. The air was sampled five minutes after the ^{133}Xe was introduced, and periodically thereafter. Results of a typical sampling sequence are shown in Table B-24.

Table B-23. Sensitivity of Eberline Model RO-2A Survey Instrument to Essentially Monoenergetic Electrons

Electron Energy (keV)	Distance (cm)	Sensitivity (mR/h)/(mrad/h)
200	30	0.09
"	20	0.2
300	30	0.3
"	20	0.3
400	30	0.4
"	20	0.4

Table B-24. Concentrations of ^{133}Xe Determined from Samples

Sampling Time	Radioactivity Concentration (nCi/cm^3)
10:36	3.18 (1.10%)
10:41	3.28 (1.07%)
10:45	3.42 (0.38%)
10:49	3.34 (1.05%)

Values of absorbed dose rates to air were calculated from the ^{133}Xe concentrations, using the conversion factors for semi-infinite clouds given in NRC Regulatory Guide 1.109, Appendix B [8]. The conversion factors consist of a beta term, taken directly from Table B-1 of the Guide, and a gamma term, to which a geometric correction factor for K x rays and 81 keV gamma rays was applied. For absorbed dose to air, the value of the total conversion factor is 1.2012×10^{-7} mrad m^3/pCi h, consisting of a beta term of 1.1978×10^{-7} and a gamma term of 3.4×10^{-10} mrad m^3/pCi h.

The results of the three immersion experiments are shown in Table B-25. Each entry for instrument response is the average of at least three readings of the instrument, and all values have been background corrected. The third column of the table indicates the total (beta plus gamma) absorbed dose rate to air, while the fourth column shows only the gamma dose rate. Those instruments that responded to only the gamma radiation are obviously the Teletector, the Xetex 305B, and the Eberline E-520. Both the Eberline PRM-7 and the Ludlum Model 16 went off-scale when exposed to the highest concentration of ^{133}Xe. Since the windows of these two instruments are too thick (see Table B-7) to admit beta rays from ^{133}Xe (E_{max} = 346 keV, $\bar{E}$ = 100 keV), they obviously responded to only the gamma radiation.

Table B-25. Response of the Survey Instruments when Immersed in ^{133}Xe Gas

Experiment Number	^{133}Xe Concentration (pCi/m^3)	Total Air Dose Rate (mrad/h)	Gamma Air Dose Rate (mrad/h)	Instrument Response					
				Teletector (mR/h)	Xetex (mR/h)	PRM-7 (μR/h)	Ludlum (cpm)	RO-2A (mR/h)	E-520 (mR/h)
3	2.16×10^{10}	2600	7.36	3.75±.14	5.18±.08	off scale	off scale	185±60	10.0±0.4
1	3.41×10^{9}	410	1.16	0.07±0.03	1.0±0.2	4100±200	510,000±10,000	37.0±1.8	1.45±.20
2	3.65×10^{8}	43.9	0.124	.0025±.0011	0.10±.05	280±10	20,750±250	13.5±1.5	0.175±.027

Evidently the only instrument that responded to the beta radiation is the Eberline Ion Chamber Survey Meter, Model RO-2A. For only the beta response, the absolute sensitivity of this instrument is approximately

$$\frac{180}{2595} \approx 0.07 \frac{\text{mR/h}}{\text{mrad/h}}$$

This is one-half the sensitivity shown in Table B-22 for the same instrument when exposed to beta particles from ^{147}Pm, which have comparable energy. The reduced sensitivity in the gaseous environment, when compared with the sensitivity indicated in Table B-22 for a confined-beam geometry, may partly be due to the fact that the entrance-window geometry of the instrument limits its response to only a fraction of the beta radiation emanating from the infinite hemisphere over which the dose rate is calculated.

3. Conclusions and Recommendations

3.1 Summary of Instrument Studies

Studies of instrument response to photon beams with energies up to 1250 keV yielded results that were both expected and unexpected. Energy dependence studies of the XETEX Model 305B showed responses that are typical for instruments that use GM tubes as detectors. Because the low-range tube is energy compensated, and the high-range tube is not, their energy dependence is significantly different (Table B-8). The Ludlum Model 16 Analyzer shows an energy dependence that is typical for instruments of this type, with a sensitivity for 70-keV photons that is 18 times higher than it is for 662-keV gamma rays (Table B-9). The Eberline Model RO-2A instrument exhibits the lack of energy dependence that is expected from ion chambers. Energy dependence of the Eberline Geiger Counter Model E-520 is typical for GM instruments, but there is also some evidence of non-linearity for higher exposure rates on some ranges (Table B-11).

Initial studies of the Eberline Model PRM-7 micro-R meter, using collimated ^{137}Cs gamma-ray beams, resulted in sensitivities that were 25 and 40 percent lower, respectively, for two instrument ranges than those given by the manufacturer.

The reason for this discrepancy was discovered to be that the manufacturer used a 4-π ^{137}Cs gamma-ray source for the initial calibration in an environment where the low-energy scatter was significant. Because this instrument has an appreciable energy dependence (the sensitivity at 70 keV is 16 times that for 662 keV gamma radiation), its sensitivity was greater in the manufacturer's calibration field, and the sensitivity control was adjusted accordingly. In the NBS field, which had no low-energy scatter component, the instrument's sensitivity was therefore lower.

Studies of the Teletector Model 6112B showed that the effect of battery condition on the instrument reading can be appreciable. On the high range, readings decreased by 14 percent when the power supply voltage decreased from 6 volts to 4 volts (the minimum indicated by the black line). In addition, there appears to be a downward trend in sensitivity for the high-range GM tube as the

exposure rate increases (Table B-16). This trend is reversed on the 2 R/h range, where the sensitivity increases with increasing exposure rate (Table B-17). Studies of energy dependence for the low-range GM tube show a sensitivity at 80 keV effective photon energy that is 2.6 times as high as the sensitivity for 250 keV photons (Table B-19).

When the instruments were exposed to ~ 6.5-MeV photons, with the detectors behind 2.5 cm of Lucite to establish electron equilibrium, the Teletector demonstrated sensitivity that was 20 percent higher than for ^{137}Cs gamma radiation. The sensitivity of the Eberline Ion Chamber Survey Meter, Model RO-2A, was also within 20 percent of that for the ^{137}Cs reference, and the sensitivity of the Xetex Model 305B instrument came to within a factor of two of this reference energy. Both of these instruments erred in the "safe" direction, i.e., their readings were higher in the ~6.5-MeV field. On the other hand, the two instruments that use NaI detectors showed readings that were low by factors of 2.5 to 3.3 (see Table B-21).

Studies of response to beta-particle beams showed that only the Eberline ion-chamber instrument, Model RO-2A, responded to beta particles over the entire energy range studied. Under the conditions chosen for the studies, it showed a sensitivity to ^{90}Y beta particles that is within 20 percent of its sensitivity to ^{137}Cs gamma-ray photons. Yet, for ^{147}Pm beta particles, its sensitivity is lower by a factor of about seven (Table B-22). Compatible results were obtained from studies of this instrument's response to monoenergetic electron beams (Table B-23).

When the six survey instruments were immersed in a ^{133}Xe gas atmosphere that represented a semi-infinite cloud, five of them apparently responded to only the gamma radiation. Evidently the only instrument that responded to the beta radiation is the Eberline Ion Chamber Survey Meter, Model RO-2A. Its absolute sensitivity for ^{133}Xe beta particles is about 0.07 (mR/h)/(mrad/h).

3.2 Conclusions Based on Study Results

The studies generally confirmed what is accepted as common knowledge regarding the performance characteristics of the various types of survey instruments. The GM instruments demonstrated their typical energy dependence, and the NaI instruments did the same, but more so. The lone ionization chamber instrument showed the flat energy response expected from that type of detector.

The discrepancy between results obtained by NBS for the Eberline PkM-7 instrument and the initial sensitivity adjustment provided by the manufacturer is a good example of a possible consequence of appreciable energy dependence. For an instrument of this type, meaningful measurement results depend upon calibration using an energy spectrum that is similar to the spectrum of the radiation to be measured in the field.

The dependence of the response of the Teletector, Model 6112B, on battery voltage may limit the usefulness of this instrument. Even though a decrease to 4.0 volts may be regarded as acceptable, the accompanying 14-percent decrease in exposure rate readings may be unsatisfactory. The difference in mean sensitivities of the various ranges of this instrument (Table B-18) is significant.

The difference in response of the various instruments to ~ 6.5 MeV photons, when each detector is placed behind 2.5 cm of Lucite, is substantial. The sensitivities, relative to the sensitivity for ^{137}Cs photons, range from ~ 3 to ~ 0.3. This order-of-magnitude difference appears to be a function of the type of detector employed.

Studies of instrument response demonstrated that only those instruments with sufficiently thin windows will respond quantitatively to beta particles. What may be interpreted as response to beta particles may instead be response to low-energy photons. Accurate measurement of beta-particle dose, using survey instruments whose primary purpose is measurement of exposure rates from photons, may be extremely difficult.

3.3 Recommendations

Although very few recommendations are made, as such, in the body of this report, the results of the various studies support some additional recommendations for consideration by NRC inspectors.

Results of the energy dependence studies show that only the ion-chamber instrument has the flat response that will result in accurate measurements regardless of the photon energy spectrum. Within its range of exposure rates, it is recommended that this type of instrument be used for quantitative measurements. Instruments that use GM or NaI detectors may be used for detection of radiation, because of their high sensitivity and fast response, but should not be used for measurements. Exceptions can be made if the energy spectrum of the field being encountered is well known, and the response of the particular GM or NaI instrument is also well known for the same energy spectrum, but this is rarely the case.

Because of the appreciable dependence of the response of the Teletector instrument on battery voltage, it is recommended that special efforts be made to replace batteries well before the voltage falls to the minimum acceptable (black-line) level.

When one of the instruments is used for surveys of radiation with energies in the vicinity of 6 MeV, it is suggested that readings be taken with increasing thicknesses of plastic placed over the detector, in order to establish an attenuation curve in plastic for the radiation field being surveyed. This is necessary because the particular radiation field of interest may differ from that used by NBS for the response studies. The attenuation curve for the field being surveyed may then be used for estimating the dose equivalents at the depths of interest (Table B-21 and Figure B-22).

Of the instruments studied, it is recommended that the Eberline Ion Chamber Survey Meter, Model RO-2A, be used for measurements of beta-particle fields. Because of the strong dependence of instrument sensitivity on the energy of the beta particles (Table B-22), such measurements must be regarded as approximations. This is particularly true if low-energy photons are also present (Table B-25).

PART C

IMPLEMENTATION OF QUALITY ASSURANCE SERVICES

E. H. Eisenhower

P. J. Lamperti

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PART C

IMPLEMENTATION OF QUALITY ASSURANCE SERVICES

Introduction

This part of the report describes the development of a program that includes a new kind of interaction between NBS and laboratories that calibrate radiation survey instruments used by NRC inspectors. The program was developed at the request of the NRC, to provide increased assurance that survey measurements made routinely by inspectors are sufficiently accurate.

At this time, the program is limited to calibrations of instruments used to measure photon (x and gamma) radiations, since these are the types most commonly encountered. The same principles can, however, be applied to beta and neutron radiations, and it is hoped that similar programs will be developed for them in the future.

1. Concepts of Measurement Quality Assurance

1.1 Basic Concepts

Measurements made to determine compliance with regulations, and thereby ensure the adequacy of radiation protection procedures, must be made with sufficient accuracy. If the measurements are sufficiently accurate, they are said to be of high quality. If high-quality measurements are desired, appropriate actions must be taken on a continuing basis to assure that the total measurement uncertainty relative to a national standard is quantified and sufficiently small to meet requirements. These collective actions constitute measurement quality assurance (MQA).

To achieve MQA, methods must be available for taking appropriate actions. Among these methods must be some that enable the measurement result obtained at the field level to be consistent with (i.e., in agreement with) the national physical measurement standards maintained by NBS.

1.2 Methods for Achieving Consistency

Over the past 50 years, the principal method used in attempts to achieve consistency has been calibration of radiation instruments or sources by NBS. These calibrated items are then used as transfer standards at an intermediate level to calibrate other sources or instruments used at the field level or, in relatively few cases, are used directly at the field level. The basic difficulty with this method is that the quality of field-level measurements is undemonstrated and is therefore unknown.

Essentially all instruments used for routine radiation protection measurements are calibrated at an intermediate level because NBS does not calibrate instruments used for that purpose. In this case, the unknown quality of the measurement arises in large part from the unknown quality of the calibration.

The calibration process is inherently limited to the measurement device, and provides no assurance of measurement quality. Consistency with the national standard is merely implied, and is not demonstrated. This fundamental limitation has become increasingly unacceptable in the radiation measurement community. As shown in the left column of Figure C-1, the consistency of the measurement must be implied because the chain of comparison ends with the instrument and does not extend to the measurement itself.

If demonstrated consistency of a measurement with a standard is desired or required, the method illustrated by the right column of Figure C-1 may be used. It is a quantitative determination of the degree of consistency because it employs an actual measurement performance test and evaluation. Demonstrated consistency is more desirable than implied consistency because it is based on a demonstration that the complete measurement process is functioning properly, including the instrument, its user, and the procedures.

Demonstrated consistency is usually achieved through utilization of a device which may be in the form of a radiation source or a dosimeter that originates from NBS or an intermediate standards laboratory. Table C-1 summarizes the procedures that are used for the various evaluations of ability to adequately perform a particular measurement function. If the participant's performance is within agreed-upon limits of accuracy, that achievement is appropriately documented.

A performance evaluation that demonstrates consistency with national standards may be provided by either NBS or an intermediate standards laboratory. Since a demonstration of satisfactory performance can not reasonably guarantee similar performance for an indefinite period of time, the demonstration process should be repeated periodically.

The right column of Figure C-1 illustrates an ideal method that results in demonstrated consistency of field-level measurements with the national standards, through services provided by an intermediate laboratory. At this time, there are only a few national programs that enable the demonstration of consistency for field-level measurements. Before the consistency-demonstration link can be made between the field and intermediate levels, however, it is necessary to establish this type of interaction between the intermediate and NBS levels. It is therefore prudent to first concentrate efforts on the development of consistency demonstration for this interaction, which will result in the mixed method shown in Figure C-2. In this case, demonstrated consistency will exist between NBS and the intermediate level, along with implied consistency between the field and intermediate levels. This method, although not ideal, represents a necessary and significant first step toward ultimate achievement of the ideal illustrated in the right column of Figure C-1.

1.3 Traceability

If the actions taken to achieve consistency with national standards are adequately documented, those documents provide evidence that specific actions were taken at a specified time. This documentary evidence that a series of actions were taken to make a field measurement consistent with a national standard is commonly referred to as traceability. A general definition of traceability is therefore "the ability to show that appropriate documented actions have been taken to demonstrate or imply that a measurement is consistent with a standard".

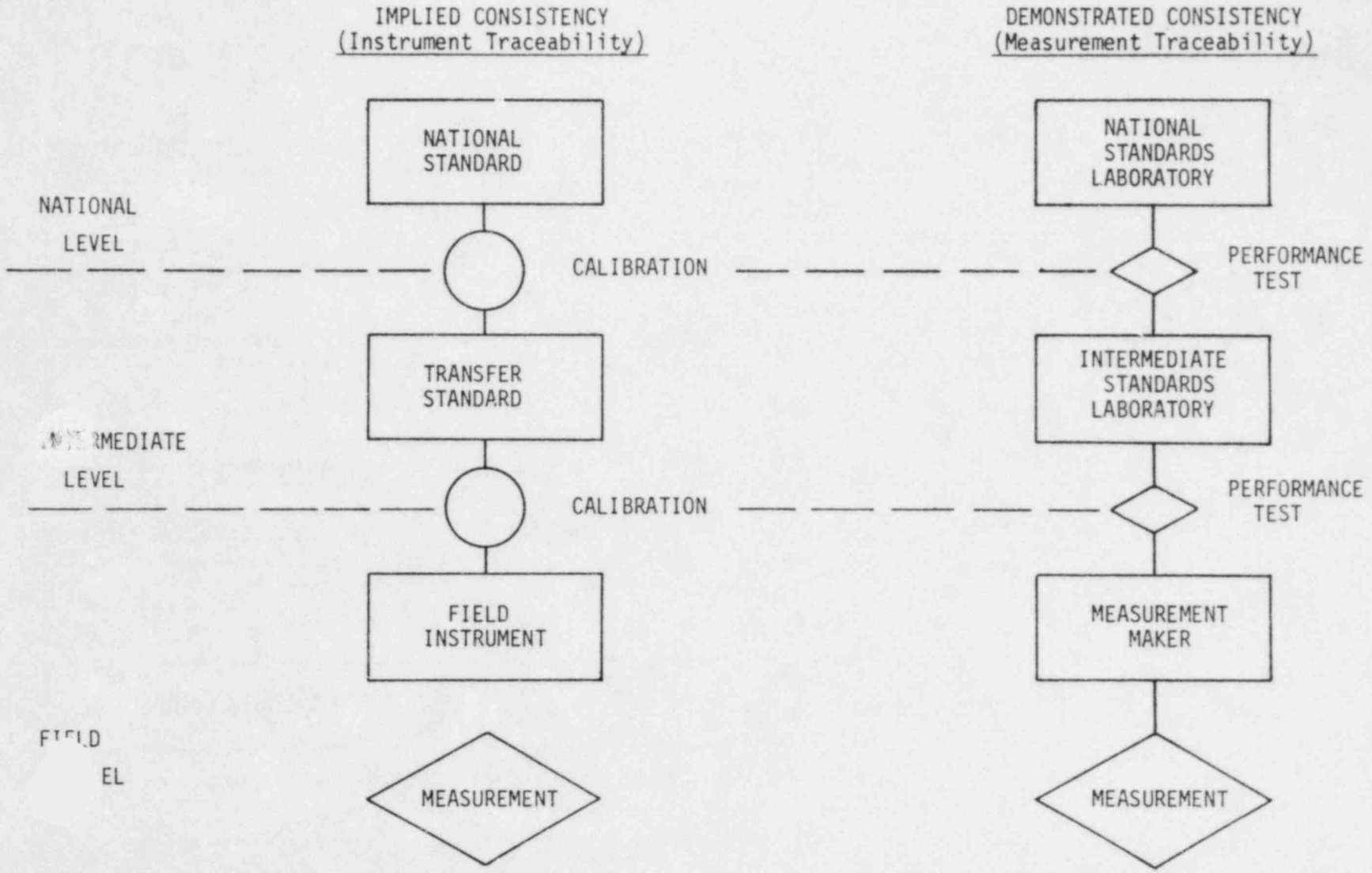

Figure C-1 Schematic Indication of the Difference between Implied and Demonstrated Consistency of a Field Measurement with the National Standard.

Table C-1

Procedures for Performance Evaluation

To Evaluate Abiiity to	Participant Should	Evaluator Should	For Evaluation by
Calibrate Dosimetry Instruments	Calibrate an Instrument	Calibrate Same Instrument	Comparison of Calibration Factors
Measure Radiation Fields (Radiation Units)	Measure an Unknown Field	Measure the Same Field	Comparison of Measurement Results
Measure Radioactivity (Activity Units)	Measure Activity of a Source	Measure the Same or an Equivalent Source	Comparison of Measurement Results
Calibrate Sources (Radiation or Activity Units)	Calibrate a Source	Calibrate the Same Source	Comparison of Calibration Results
Administer Radiation Dose	Administer a Nominal Dose to a Dosimeter	Calibrate and Read-out the Dosimeter	Accuracy of Administered Dose
Read-out Dosimeters	Calibrate and Read-out a Dosimeter	Administer a Known Dose to the Dosimeter	Accuracy of Read-out Dose

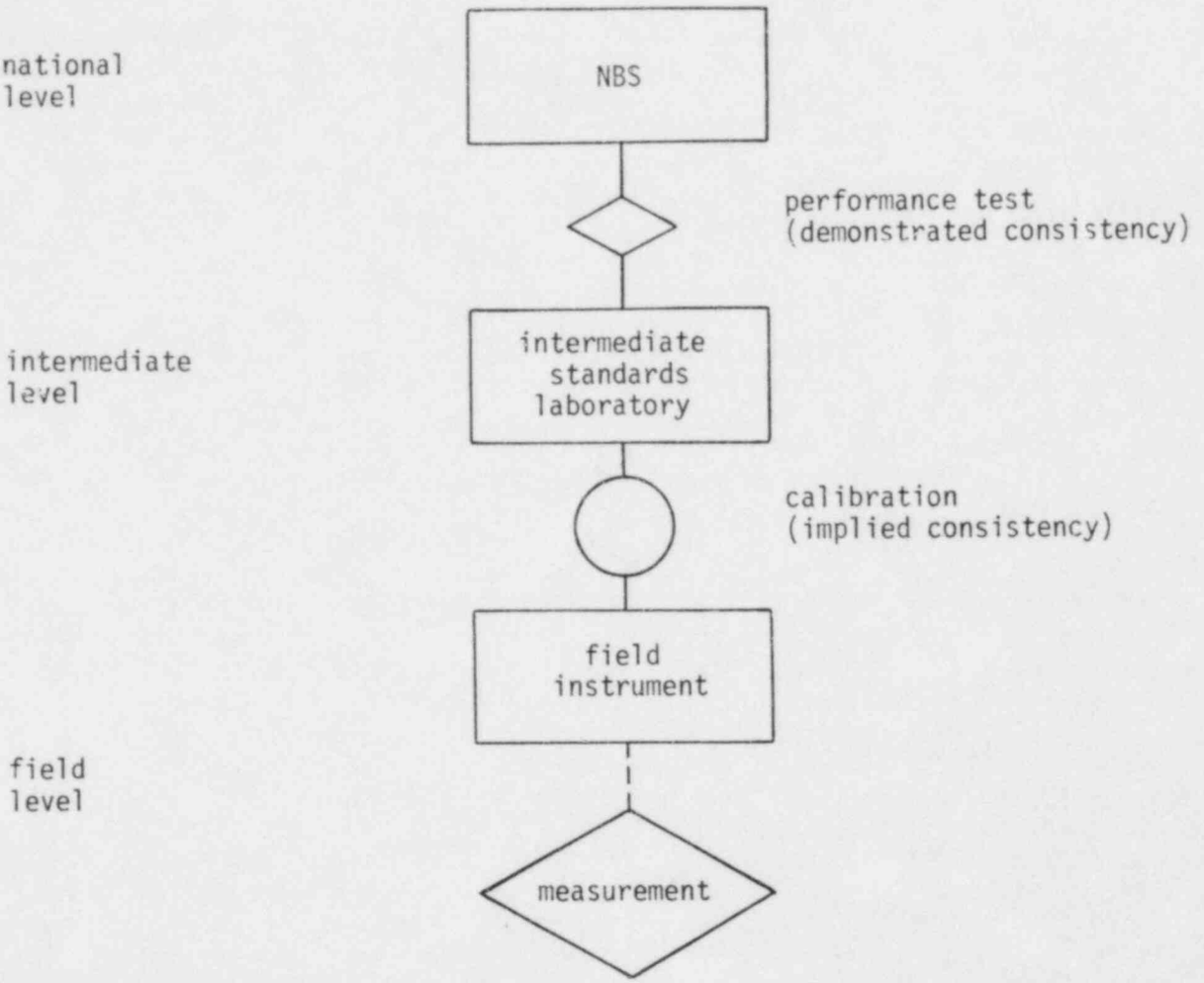

Figure C-2. Schematic Indication of a Method that Involves both Demonstrated and Implied Consistency.

More specific definitions of traceability, corresponding to either implied or demonstrated consistency, are possible. The documentary evidence resulting from the calibrations that provide implied consistency may be called "instrument traceability". It is the ability to show that a particular instrument (or radiation source) has either been calibrated using the national standard or has been calibrated using a transfer standard in a chain or echelon of calibrations ultimately leading to a comparison with the national standard. In this case, traceability takes the form of one or more calibration certificates or reports.

When consistency with a national standard is demonstrated, the results of the performance evaluation are stated in a letter or report from the laboratory that conducted the evaluation. This documentary evidence constitutes what may be called "measurement traceability", which is the ability to show that a performance evaluation was employed to demonstrate measurement results that were consistent with the national standard.

1.4 Measurement Quality Assurance Program

To provide a reasonable degree of assurance that performance remains satisfactory at all times, the measurement maker at the field level or at the intermediate standards laboratory should have a measurement quality assurance program. Such a program can include a variety of periodic actions, depending upon the specific nature of the measurement. In a general sense, an MQA program consists of procedures that enable a measurer to assure on a continuing basis that the total measurement uncertainty relative to the national standard is quantified and sufficiently small to meet requirements. It can include internal constancy checks, such as the frequent use of stable radiation sources to check instrument response, and control charts that would warn of unusual response or instability in the measurement process. An important element in an MQA program is, of course, the periodic external performance evaluation that maintains demonstrated consistency with the national standard.

Figure C-3 illustrates the essential principles and procedures of an MQA program that includes periodic interaction with NBS. In this case, the participant is assumed to be an intermediate standards laboratory that routinely calibrates dosimetry instruments for users at the field level. As a result, the first row of Table C-1 applies and the comparative device takes the form of a dosimetry instrument. Upon initiation of this interactive MQA program, the participant's in-house reference standard would be calibrated by NBS. As long as subsequent internal constancy checks and external performance evaluations produced satisfactory results, this transfer standard would never again need to be recalibrated.

1.5 Documentation

As indicated by the lower third of Figure C-3, this example of an interactive MQA program results in demonstrated consistency with NBS that is appropriately documented. In general, the additional types of documents that should be prepared for an intermediate laboratory's MQA program are: (1) the procedures used for the periodic consistency demonstration with NBS (performance evaluation); (2) the routine in-house quality control procedures; and (3) the procedures used for providing routine services. This complete set of documentation, along with the procedures outlined in Figure C-3, will provide a very high degree of assurance that an intermediate standards laboratory performs adequately in a continual manner.

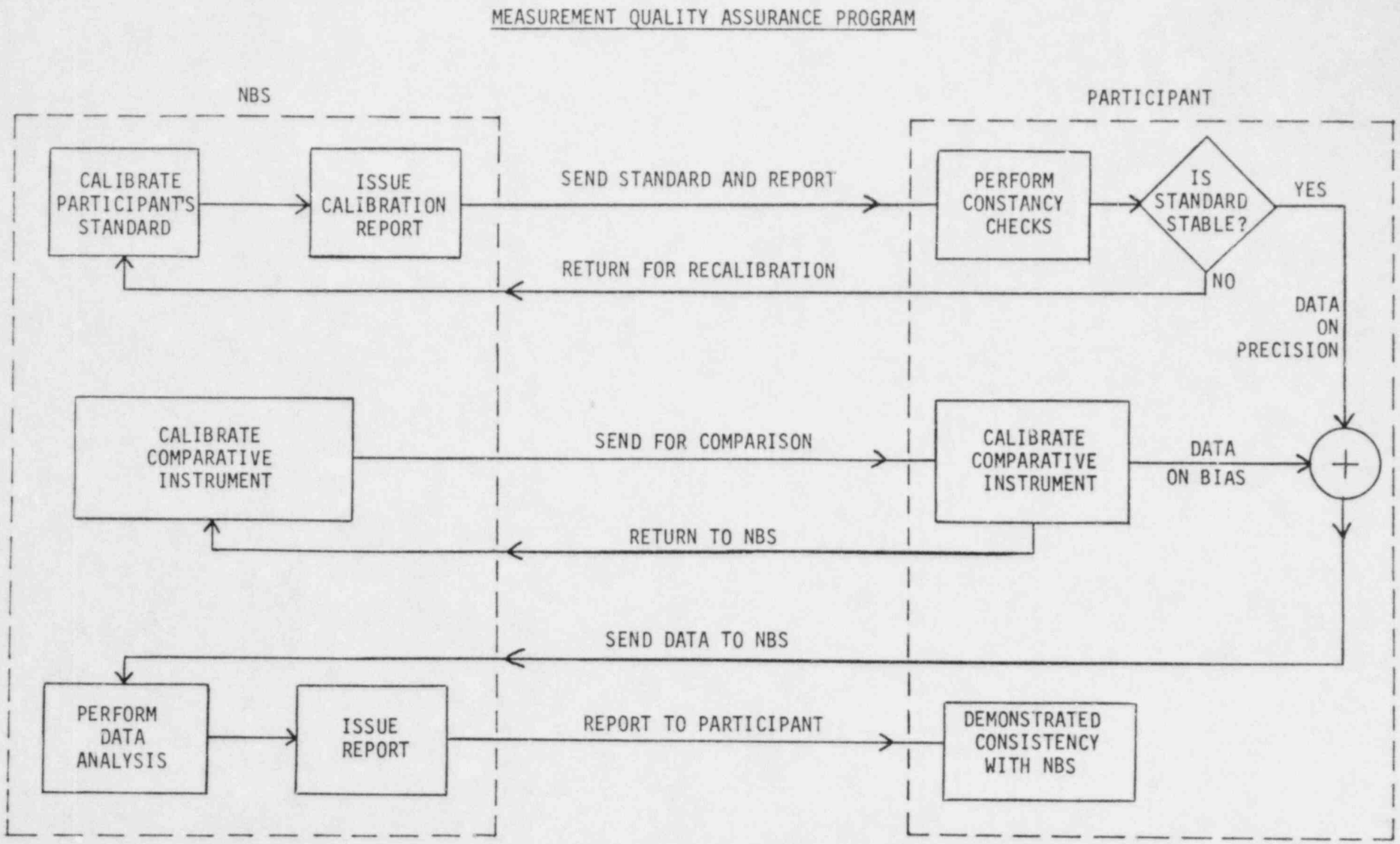

Figure C-3 Illustration of the Principles and Procedures of an Interactive Measurement Quality Assurance Program.

2. Contacts with NRC Contractor Laboratories

At the beginning of this project, NBS was asked to provide consistency demonstration services to four laboratories that either were calibrating survey instruments for NRC inspectors or would be in the future. The laboratories initially identified were Argonne National Laboratory, Brookhaven National Laboratory, Eberline, and Lawrence Livermore National Laboratory. Each was contacted to determine its interest in participating in services that would result in demonstrated consistency with NBS.

2.1 Argonne National Laboratory

On January 26, 1981, two NBS staff members visited Argonne National Laboratory (ANL) to discuss the possibility of establishing measurement quality assurance (MQA) interactions. Discussions were held with members of the ANL health physics group and the electronic maintenance shop which supports that group. At this time, instruments used by NRC inspectors are calibrated in the electronics shop, using radiation sources owned by the health physics group. New calibration facilities are being established in another building, but progress is slow due to lack of funds.

Present facilities include approximately 25 curies of cobalt-60 in a source used to calibrate instruments at a distance of about 100 cm. This provides an exposure range of 50 mR/h to 10 R/h, with the use of absorbers to change exposure levels. For lower exposure levels, there is a 1-mg radium source that provides a range from 2 mR/h to 20 mR/h, at distances from about 7 to 20 cm.

The ANL health physics staff members were generally in favor of establishing MQA interactions with NBS, and a suitable program will be implemented.

2.2 Brookhaven National Laboratory

Initial contact with Brookhaven National Laboratory (BNL) was made via telephone on August 14, 1981. After the nature and purpose of the proposed MQA interactions were described to the person in charge of the BNL calibration laboratory, he responded favorably but indicated the need for conferring with higher management before responding officially. On August 24, he responded via telephone that BNL does desire to participate in MQA interactions with NBS. At this time, interactions are desired for gamma radiation from cesium-137 and cobalt-60.

2.3 Eberline (a division of Thermo Electron Corporation)

On September 9, 1981, the Southeast Service Center of Eberline was visited in Columbia, South Carolina, and discussions were held with the manager of the laboratory. This facility calibrates survey instruments for NRC inspectors in Region II.

The gamma calibrations are performed with three cesium-137 sources, with activities of 10 mCi, 10 Ci, and 1000 Ci. These provide exposures ranging from 0.7 mR/h to slightly over 400 R/h. The two larger sources are in vertical 10-inch diameter steel pipes surrounded by concrete shields. Whe not in use, the sources are stored about 7 meters below the point where instruments are placed for calibration. The intensity of the field depends upon the location

of the source in the pipe, which is controlled by a chain that runs over a pulley operated by a hand crank. A counterweight on the other end of the chain balances the weight of the source. The 10-mCi source is used without collimation at one end of a long wooden-topped table, on which the instrument is placed for calibration a known distance from the source. A third concrete bunker contains 7.65 Ci of ^{238}Pu-Be used as a source for neutron calibrations. A variety of alpha and beta sources are available for instrument calibrations. These are the electroplated, μCi-level sources that Eberline sells as certified standards.

The laboratory visit was preceded by telephone contact with the Eberline home office on August 14, at which time the proposed interactive program was described to the Manager of Instrument Division Services. In a letter dated August 17, he requested that three Eberline calibration laboratories, including the Southeast Service Center, be involved in future MQA interactions for photon, alpha, and beta radiation.

2.4 Lawrence Livermore National Laboratory

An NBS staff member visited Lawrence Livermore National Laboratory (LLNL) on March 27, 1981, to discuss with representatives of their dosimetry group the possibility of establishing MQA interactions. The laboratory is well-equipped and highly automated, and is described in detail in a report entitled "Tour of the Standards and Calibrations Laboratory" [14]. The facilities and equipment include:

A low-scatter cell where either a neutron generator (14 MeV and 2.8 MeV), neutron sources (several Pu-Be, ^{252}Cf, PuLi), or gamma sources (cobalt, cesium, americium) can be used. The sources are brought into the room by a pneumatic source-transfer system.

A cobalt-60 irradiation pool about 2 m in diameter and 6 m deep.

A beta-source range with sources that offer a wide choice of energies.

A manganous-sulfate bath for neutron source calibrations.

Free-air ionization chambers.

A 150-kV, 10-mA x-ray system, with fluorescence capability.

An X-ray system that has three transmission anode x-ray tubes for characteristic radiation from copper, silver, and neodymium anodes. These tubes were developed at LLNL.

Neutron moderators including polyethylene, water, D_2O, and solid aluminum.

A large variety of detectors and counters.

During the discussions, a strong desire to implement MQA interactions with NBS was indicated by LLNL representatives, including various types of radiation. Initial interactions will be limited to photon radiation.

2.5 Other Laboratories

Subsequent to the initial identification of the four laboratories by the NRC, it was requested that Lawrence Berkeley Laboratory and the Radiological and Environmental Sciences Laboratory be added. Both laboratories were contacted, and both expressed an interest in establishing MQA interactions with NBS.

Although the Battelle Pacific Northwest Laboratory is not among the laboratories that currently calibrate instruments for NRC inspectors, the possibility of MQA interations with BPNL was investigated, with positive results. Therefore such interactions for photon radiation will also be extended to this laboratory at this time. In the future, BPNL desires to have MQA interactions with NBS for beta and neutron radiations, as well as photons.

3. Request for Information

To obtain the information required for the planning and conduct of consistency demonstration services, a questionnaire was distributed to the potential participants (see Appendix C-1). The questionnaire asked for essential characteristics of the photon beam(s) used by the participating laboratory, a description of the laboratory's in-house standard, the maximum acceptable difference between NBS and the laboratory's results, desired frequency of NBS consistency demonstration services, and status or intentions regarding in-house constancy checks.

As of March 1, 1984, completed questionnaires had been received from Argonne National Laboratory, Eberline, Lawrence Livermore National Laboratory, and the Radiological and Environmental Sciences Laboratory (RESL).

3.1 Photon Beam Characteristics

So that an appropriate performance evaluation could be designed, prospective participants were asked to describe the characteristics of the photon beam(s) they would use to calibrate the instrument circulated by NBS. For x-ray beams, the characteristics of importance are generating potential, first and second half-value layers, exposure or dose rate, and size of the field at the calibration position. For beams produced by radionuclides, the essential characteristics are the particular radionuclide, the exposure or dose rate, and the field size.

Only one respondent (Livermore) expressed an intention to use x-ray beams, and characterized them in terms of the NBS beam codes at exposure rates ranging from 10 to 1000 R/h. The four respondents specified ^{137}Cs as a radionuclide they intended to use, with desired exposure rates from 0.1 mR/h to 1000 R/h. Two responding laboratories (Argonne and Livermore) specified ^{60}Co, at exposure rates of 1 R/h and 5 R/h.

3.2 In-House Standards

The prospective participants were asked to describe their in-house standards, and to provide the date of the last calibration by NBS. The four respondents use a variety of ionization chambers as their reference standards. Dates of last calibration by NBS ranged from 1975 to 1983.

3.3 Maximum Acceptable Difference

Since consistency demonstration services are provided by NBS to satisfy the participants' needs, the desired degree of consistency should be determined by each participant. Therefore, each prospective participant was asked to state the maximum acceptable difference between the calibration factors determined by NBS and by the participant. In terms of percent difference, both Argonne and Eberline stated ±10 percent as the maximum acceptable, while Livermore stated 3 percent for x rays and 2 percent for gamma rays, and RESL stated 3 percent for cesium-137 gamma rays.

3.4 Frequency of Consistency Demonstration

Until a participating laboratory has established a history of demonstrated consistency with the national standards, it may be desirable to use NBS consistency demonstration services more frequently. When a sufficient history has been established, the frequency of participation may be decreased. Given this condition, each prospective participant was asked the desired frequency of participation over the next year or two. Livermore requested a frequency of every 12 months, while Argonne, Eberline, and RESL requested every six months.

3.5 In-House Constancy Checks

Since constancy checks are an important element of a calibration laboratory's measurement quality assurance program, the prospective participants were asked to indicate their status or intentions regarding such checks. It is encouraging that all respondents indicated an intention to conduct constancy checks. Livermore and RESL responded that they are not currently performing constancy checks but would begin doing so if recommended methods were available. Both Argonne and Eberline indicated they are currently performing constancy checks and are willing to participate in a cooperative effort to prepare suitable recommended methods, along with RESL.

4. Development of Services

As shown in Figure C-3, periodic demonstration of consistency with NBS is only one element of a calibration laboratory's overall measurement quality assurance program. Specific consistency demonstration services should therefore be developed in a manner compatible with the total MQA program.

4.1 Recommended MQA Program

It is recommended that the laboratories that calibrate survey instruments for NRC inspectors adopt an MQA program as follows.

(1) The calibration laboratory and NBS will agree on the radiation qualities and the exposure or absorbed dose rates for which a joint MQA program will be carried out. The calibration laboratory will inform NBS of the maximum acceptable difference determined through NBS consistency demonstration services. This maximum value should be set realistically, bearing in mind the purposes of the calibration laboratory as well as the cost of achieving high accuracy.

(2) NBS will calibrate the laboratory's in-house standard ionization chamber(s), for the agreed-upon radiation qualities and rates. Constancy checks on these standards will be performed by the calibration laboratory immediately before and after NBS calibration, and at suitable intervals thereafter.

(3) Consistency with the national standards will be demonstrated through periodic NBS consistency demonstration services. These will consist of circulation of suitable ionization chambers from NBS to the participating laboratory for calibration and return, and subsequent comparison of calibration factors. These services will not be used to establish calibration factors for the in-house standards. A cumulative record will be maintained, by NBS and by the calibration laboratory, on performance of the calibration laboratory as determined by the consistency demonstration service. This record will demonstrate consistency in a broader sense--not only in terms of agreement with NBS, but also in terms of continued satisfactory performance.

(4) Constancy checks on the stability of the in-house standard and the consistency of the calibration procedures will be carried out by the calibration laboratory. These checks should make use of long-lived radioactive sources and highly reproducible measurement procedures, as well as comparison of every routine repeat measurement with its expected value. Accumulation of long-term records is the most effective method for confirming stability of instruments and consistency of procedures.

(5) If the in-house constancy checks and the consistency demonstration results are within the stated acceptable limits, the in-house standard will not be recalibrated. If the acceptable limits are exceeded, steps will be taken by NBS and by the calibration laboratory to determine the cause. If the in-house standard is for any reason suspect, it will be returned to NBS for recalibration.

The MQA program recommended above is intended to supersede the conventional program of periodic recalibration of the in-house standard ionization chamber. The in-house standard should not be returned for recalibration until there is adequate reason to do so. NBS will however necessarily charge a fee for the periodic consistency demonstration services.

Constancy checks on the in-house standard and on the calibration procedures are an essential aspect of the proposed MQA program and are the responsibility of the calibration laboratory. Redundancy is the key to reliable calibration, and a well-designed constancy check procedure should involve some redundancy. It is expected that protocols on recommended methods of performing constancy checks on in-house standards and on calibration procedures will be made available in the future as the result of work by NBS and other organizations.

4.2 Consistency Demonstration Services

It is planned to provide consistency demonstration services to all calibration laboratories that wish to take advantage of such services. If each laboratory were served individually, however, NBS might be overwhelmed by the increased workload caused by calibration of instruments used for consistency demonstration. In order to carry out this program, the laboratories will be grouped together according to their beam qualities, so that a single set of

consistency-demonstration instruments can be sent to several laboratories in succession, without intermediate return to NBS. By reducing the calibration burden in this manner, it is hoped to improve the NBS response time and keep the cost at a reasonable level.

With this aim in mind, the procedures to be followed for consistency demonstration were developed as described in Appendix C-2. Those detailed procedures can be described in a simplified manner as follows:

(1) Three ionization chambers, an electrometer, a constant-current source, and connecting cables are sent to the participant.

(2) The participant performs prescribed constancy checks that determine whether critical characteristics of the instruments were altered during shipment.

(3) If the constancy checks (ratios of ion chamber currents) are satisfactory, the calibration measurements may proceed.

(4) The participant calibrates two or three of the ion chambers at suitable photon energies and intensities, and reports the correction (calibration) factor to NBS.

(5) The instruments are shipped to the next participant, where the same procedures are followed.

In accordance with these procedures, the instruments were shipped to the first participant, Argonne National Laboratory, in mid-January 1984.

5. Conclusions and Recommendations

The favorable response from the laboratories contacted since the start of this project, and the successful initiation of consistency demonstration services by NBS, lead to the conclusion that the proposed interactive measurement quality assurance program is desirable and feasible. As a result, it is recommended that the laboratories that calibrate survey instruments for NRC inspectors adopt the MQA program described in Section 4.1 of this part. The program should first be adopted for photon radiations, after which it should be extended to other types of radiation, such as beta particles and neutrons.

APPENDIX C-1

Request for Information

To: Potential Participants in NBS Measurement-assurance Services for Radiation Dosimetry

The information requested below is required for the planning and conduct of your measurement-assurance service and applies only to dosimetry for photon radiation (x and gamma rays).

A. Characteristics of the photon beam(s) that you will use to calibrate the instrument circulated by NBS:

Beam Quality					
		Al Cu (delete one) Half-value layer			
Generating Potential	Wave Form	First	Second	Exposure or Dose Rate	Field Size at Calibration Position

Radionuclide

B. Description of your in-house standard(s):

Manufacturer	Model No.	Chamber Volume	Last NBS Calibration Date	DG Number

C. If "error" is defined as the difference between the calibration factors determined by NBS and by your laboratory, respectively, what is the maximum you will find to be acceptable? State in terms of percent difference:

D. Until a participating laboratory has established a history of demonstrated consistency with the national standards (within the acceptable limits of error), it may be desirable to use NBS measurement-assurance services more frequently. When a sufficient history has been established, the frequency of participation may be decreased. At what frequency do you desire to participate for the next year or two? (Check one.)

- ☐ every 6 months
- ☐ every 12 months
- ☐ other (explain)

E. Indicate your status or intentions with regard to in-house constancy checks: (Check all that apply.)

- ☐ do not intend to perform constancy checks
- ☐ am currently performing constancy checks
- ☐ am not currently performing constancy checks but would begin doing so if recommended methods (protocols) were available
- ☐ am willing to participate in a cooperative effort to prepare suitable protocols
- ☐ other (explain)

_____ _____

Name Date

Please return this completed questionnaire, at your earliest convenience, to:

Dosimetry Group
Attn: R. Loevinger
Radiation Physics C210
National Bureau of Standards
Washington, DC 20234

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

MQA 012/84
1984 Jan 12

Protection-level Measurement Quality Assurance Test

Redundant measurement equipment is supplied in this MQA test so that the equipment can be checked for constancy before the quality assurance measurements are started.

Equipment list

Keithley constant-current source, Model 261, SN 21813
Keithley electrometer, Model 35020, SN 6187
Keithley ion chamber, Model 96020, SN 1750, and plane buildup cap
Keithley ion chamber, Model 96020A, SN 8190, and plane buildup cap
Keithley ion chamber, Model 96035, SN 7904, and 2 plane buildup caps
Signal-lead connector cap for each chamber
Triax cable, 68 cm long
Coax cable, 15 m long
Chamber stem holder

Outline of constancy-check procedure

(1) Polarizing voltage: 216 V

(2) Charge response of K35020:
K261: -5.00×10^{-11}
K35020: (1.20 ± 1) mR/s

(3) Current response of K35020:

K261:	-7.1×10^{-12}	-7.1×10^{-11}	-7.1×10^{-10}	-7.1×10^{-9}
K35020:	10.14 ± 2	101.1 ± 2	1013 ± 2	10200 ± 20

(4) Ratio of chamber currents:

	^{137}Cs	^{60}Co		^{137}Cs	^{60}Co
$\frac{96020}{96035}$:	10.31	10.34	$\frac{96020A}{96035}$:	10.60	10.67

(5) If any of these constancy checks differs from the NBS value by an amount that you consider significant, contact

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Details of constancy-check procedure

(1)
- Plug in K261, set switch in the straight-up OFF position.
- Plug in K35020, set zero switch to LOCK, power switch to ON.
- Connect output of K261 to input of K35020, using triax cable supplied.
- Check polarizing voltage on rear binding posts of K261. The NBS reading was 216 V. The black post is +. DO NOT SHORT THESE BINDING POSTS.

(2) After a warm-up of about 20 minutes, check the charge response of the K35020 as follows:

- Set K261 to -5.00×10^{-11}.
- Set K35020 to DOSE mode, AUTO sensitivity, background suppression off, altitude switches to 0.
- Prepare suitable timer.
- Set K35020 to PUSH TO RESET, and start timer at 30 mR. After 5 or more minutes, end the measurement at a convenient reading. The NBS number for this procedure was (1.20 ± 1) mR/s.
- Set zero switch to LOCK.

(3) Check the current response of the K35020 as follows:

- Set K261 to -7.1×10^{-12}.
- Set K35020 to LOCK zero, RATE mode, AUTO sensitivity, background suppression off, altitude switches to 0.
- Set display to 0.000 ± 1 digit using zero ADJUST.
- Set zero switch to PUSH TO RESET and record the display for the following settings:

K261:	-7.1×10^{-12}	-7.1×10^{-11}	-7.1×10^{-10}	-7.1×10^{-9}

The corresponding NBS readings were

K35020:	10.14 ± 2	101.1 ± 2	1013 ± 2	10200 ± 20

- Set zero switch to LOCK.

(4) Determine the ratios of the currents for the three chambers, using ^{60}Co and/or ^{137}Cs beams that include not more than about 10 cm of cable. Use the plane buildup caps supplied.

The ratios at NBS were as follows:

	^{137}Cs	^{60}Co		^{137}Cs	^{60}Co
$\frac{96020}{96035}$:	10.31	10.34	$\frac{96020A}{96035}$:	10.60	10.67

These ratios can be determined at any convenient exposure rate. At very high exposure rates, correction for volume recombination loss may be necessary. The collection efficiency at 216 V is given by $f = 1 - k\dot{X}$, where $\dot{X}$ is in R/h, and

k =	2.0×10^{-7}	25×10^{-7}	5.1×10^{-7}
for chamber	96035	96020	96020A

Measurement Protocol

(1) Instrument Preparation

Turn on power to K35020 with zero switch in LOCK position.

Connect input to chosen chamber using coax cable supplied.

Mount chamber and cable in chamber stem holder and secure with tape, as necessary.

Align chamber in the beam with front window facing the source and perpendicular to the beam. (The front window has screw heads showing near the edge.) For setting distance, the reference plane is the mid-plane of the chamber.

For gamma-ray calibrations only, use the buildup caps supplied, one each for chambers K96020A and K96020, and two for K96035. Note that the active area of the K96035 is about 40 mm in diameter and is located off center. Its position is marked on the front buildup cap.

(2) Calibration Measurements

Calibrate two or three of the chambers under normal calibration conditions.

Use either the RATE or the DOSE mode. The RATE mode is more convenient, and apparently adequately accurate. Use AUTO sensitivity, background suppression off, altitude switches at 0.

Normalize readings to 22°C and one standard atmosphere (101.325 kPa, 760 mmHg).

The electrometer should have had about a 30-minute warm-up before taking serious measurements.

(3) Additional Information

Chambers K96020A and K96020 have been calibrated for all NBS beam qualities from M30 to M300 and H30 to H300, and for ^{137}Cs and ^{60}Co gamma rays. Chamber K96035 has been calibrated only for ^{137}Cs and ^{60}Co. Your x-ray beam qualities must be consistent with the NBS M or H qualities, if a valid interpretation is to be possible.

This equipment can be used for exposure rates from about 50 mR/h up to about 10^3 R/h for x-ray beams, and up to about 10^4 R/h for gamma-ray beams.

Chamber K96020 has a somewhat longer equilibration time than the other chambers. The polarizing voltage must be on this chamber for some minutes before stable readings are possible.

The NBS calibrations were performed in beams that were only a few centimeters larger than the chamber.

If problems arise during the measurements, they can be discussed with Paul Lamperti at 301/921-2361.

(4) Report the results in terms of dimensionless correction factors:

$$\text{correction factor} = \frac{\text{your value of exposure rate}}{\text{indicated exposure rate}}$$

If you are testing x-ray beams, give the correction factors for your beams, and also estimated values for NBS beam qualities, if possible. For each correction factor, report the following:

- Peak kV or γ-ray energy
- For x rays, 1st and 2nd half-value layer, in both Al and Cu, if possible
- Distance, source to reference plane
- Approximate beam size at chamber
- Approximate exposure rate at chamber

Also report results of the constancy-check tests.

(5) Shipping

The shipping container is reusable. Return to NBS or ship to next participant, according to directions from Paul Lamperti.

Appendix C-3

GLOSSARY OF TERMS

accuracy - a measure of the ability of a measurement process to obtain closeness to the true value

calibration - (see "instrument calibration" or "source calibration")

comparative device - an instrument, dosimeter, or radiation source that is used to demonstrate consistency (agreement) of measurement results obtained by two measurers

consistency - agreement of a measurement result with the appropriate national standard to within a specified level

consistency demonstration - use of a comparative device to obtain measurement results that are in sufficient agreement with a national standard

consistency demonstration service - a service provided by NBS or by an intermediate standards laboratory to obtain measurement results from a participant that are in sufficient agreement with a national standard

constancy checks - use of a source of radiation or electrical charge to produce an observable response by an instrument, for comparison with previous responses to the same source under the same conditions

demonstrated consistency - the achievement of measurement results, when performance is evaluated using a comparative device, that are in sufficient agreement with a standard

implied consistency - the achievement of measurement results that are not demonstrated to be in agreement with a standard

in-house standard - an instrument or radiation source that was calibrated by NBS and is used as a reference for calibrations performed by an intermediate standards laboratory

instrument calibration - a comparison of the response of a given instrument with the response of a standard instrument when both are exposed to the same radiation source under the same conditions; or the determination of the response of a given instrument when exposed to the output of a standard source under well-defined conditions

instrument traceability - the ability to show that a particular instrument or radiation source has either been calibrated using the national standard or has been calibrated using a transfer standard in a chain or echelon of calibrations ultimately leading to a comparison with the national standard

maximum acceptable difference - a previously-agreed-upon limit to the amount by which a participant's measurement result may differ from the result obtained by the laboratory providing a consistency demonstration service. If the service is provided by NBS, for example, the difference is

$$\left|\frac{\text{participant's value - NBS value}}{\text{NBS value}}\right| \times 100\%$$

measurement quality assurance - those actions that enable a measurer to assure on a continuing basis that the total measurement uncertainty relative to a national standard is quantified and sufficiently small to meet requirements

measurement traceability - the ability to show that a performance evaluation has been employed to demonstrate measurement results that are consistent with a national standard

national standard - the physical realization of the international definition of a measurement unit for use as a national reference

source calibration - determination of the output of a radiation source by comparison with the output of a standard source, or by the response of a standard instrument to the output of the source

traceability - the ability to show that appropriate documented actions have been taken to demonstrate or imply that a measurement is consistent with a standard

transfer standard - a physical measurement standard that has been compared directly or indirectly with the appropriate national standard

uncertainty - an estimate of the limits to the error of a measurement result

DG 8238/84/ANL
1984 Apr 19

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, DC 20234

REPORT OF

MEASUREMENT QUALITY ASSURANCE TEST
FOR THE QUANTITY EXPOSURE

Participant: Argonne National Laboratory
Calibration Facility

Test equipment: Keithley electrometer Model 35020, SN 6187
Keithley chambers Model 96020, SN 1750;
Model 96020A, SN 8190; and Model 96035, SN 7902
Keithley constant current source Model 261, SN 21813

A measurement quality assurance (MQA) test of a calibration laboratory determines the agreement between instrument calibrations performed by that laboratory and calibrations performed by NBS. Suitable instruments are calibrated by NBS and then sent to the calibration laboratory, where they are tested for constancy in accord with procedures formulated by NBS, and then calibrated. The result is reported in terms of the ratio "Institution CF divided by NBS CF". In this ratio, "CF" indicates a calibration factor or a correction factor; a calibration factor is the quotient of the measured exposure rate in air by the signal from the instrument, and a correction factor is the ratio of the measured exposure rate in air to the exposure rate indicated by the instrument. Calibration factors have the units roentgens per coulomb (R/C) in these tests, and correction factors are dimensionless. The results of an MQA test apply only to the specific beams and irradiation conditions used by both NBS and the participating calibration laboratory.

An MQA test for Co-60 gamma-ray beams was performed by personnel of Argonne National Laboratory (ANL) during 1984 Feb 6-17. The ANL data were reported to NBS in a letter from E. H. Dolecek dated 1984 Mar 27. The NBS data are contained in NBS Reports of Calibration DG 8169/83 and DG 8369/83. For the Co-60 beams used, the ratios of the ANL correction factors to the NBS correction factors are as follows:

Ionization Chamber	ANL CF / NBS CF
K96020	0.973
K96020A	0.973
K90635	0.963

For the specified radiation beam, these ratios demonstrate agreement between ANL and NBS calibrations that is within the ±10% desired by ANL.

Information on technical aspects of this report may be obtained from P. J. Lamperti, Radiation Physics C210, National Bureau of Standards, Washington, DC 20234, (301) 921-2361.

Measurements performed by P. J. Lamperti PL

Report approved by R. Loevinger RL

For the Director
By

William R. Ott
Chief, Radiation Physics Division
Center for Radiation Research
National Measurements Laboratory

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16. ABSTRACT *(200 words or less)*

This report describes results of a three-year program that will enable the Nuclear Regulatory Commission to improve, demonstrate, and document traceability of its measurements to the national physical measurement standards for ionizing radiation. The principal actions taken were: (a) characterization of the response of a thermoluminescence dosimetry system used for routine surveillance of nuclear facilities; (b) characterization of the response of six models of portable survey instruments; and (c) implementation of routine quality assurance services that will demonstrate that laboratories which calibrate survey instruments for the NRC are sufficiently consistent (in agreement) with national measurement standards. Tests of the TLD system were performed as specified in American National Standard N545-1975, plus several additional tests not contained in that document. Measurement assurance tests were conducted for the NRC Region-1 laboratory. The response of the survey instruments was determined for photon energies as high as 6.5 MeV, and for beta particles of various energies, including those emitted by ^{133}Xe gas. The basic principles under which the long-range interactive MQA program will operate were developed and documented, and the feasibility of the program was demonstrated.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

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