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Performance Testing of Extremity Dosimeters, Study 2

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ABSTRACT

The Health Physics Society Standards Committee (HPSSC) Working Group on Performance Testing of Extremity Dosimeters has issued a draft of a proposed standard for extremity dosimeters. The draft standard proposes methods to be used for testing dosimetry systems that determine occupational radiation dose to the extremities and the performance criterion used to determine compliance with the standard.

Pacific Northwest Laboratory (PNL) has conducted two separate evaluations of the performance of extremity dosimeter processors to determine the appropriateness of the draft standard, as well as to obtain information regarding the performance of extremity dosimeters. The results of the first set of performance tests (conducted in 1987) indicated that approximately 60% of the time the processors met the performance criterion for accuracy (as expressed by the bias) and precision (as expressed by the standard deviation) at the tolerance level specified in the draft standard. Because of these results, the U.S. Nuclear Regulatory Commission (NRC) requested that PNL investigate the sources of error that may have occurred during the performance testing. The results of that investigation are summarized in this report. PNL discovered that for two processors, major errors occurred as a result of poor procedures or equipment malfunctions. In addition, several processors indicated that they were not as prepared for this test as they could have been, and that their performance would likely improve on subsequent tests.

Thus, a second test study (summarized in this report) was conducted with the same 11 processor facilities that participated in the first test study, and a total of 22 types of extremity dosimeters. Dosimeter performance was tested in the seven irradiation categories specified in the draft standard: low-energy photons (general and accident dosimetry), high-energy photons (general and accident dosimetry), beta particles, neutrons, and a mixture category. The results indicate that approximately 70% of the time the ring dosimeters passed and 81% of the time the wrist dosimeters passed, at the tolerance level specified in the draft standard. This is an overall improvement of 15% to 18% from the results of the initial performance test (comparing the results obtained using similar sources). However, the results indicated that most processors were unable to meet the performance criterion consistently for all irradiation categories. For example, the passing rates in the beta-particle categories (for ring dosimeters) and the neutron category (for wrist dosimeters), were 45% and 63%, respectively. Variations in the results were also observed within a specific category as a function of the source (or energy) that was used. The most significant difference between sources (or energies) was observed for ring dosimeters irradiated in the low-energy photon category (NIST filtered techniques H150 and M150) and in the beta particle category ($^{90}Sr/^{90}Y$ and ^{204}Tl). For the wrist dosimeters, significant differences between sources were observed in the low-energy photon category (NIST filtered techniques H150 and M150) and in the neutron category (moderated ^{252}Cf and unmoderated ^{252}Cf).

Based on the information obtained during the facility visits and the results obtained from the performance testing, it was recommended that changes be made to ensure that the draft standard is appropriate for extremity dosimeters. The changes include:

- subdividing the mixture category and the beta particle category,
- eliminating the neutron category until appropriate flux-to-dose equivalent conversion factors are derived, and
- changing the tolerance level for the performance criterion to provide consistency with the performance criterion for whole body dosimeters, and to avoid making the draft standard overly difficult for processors of extremity dosimeters to pass.

SUMMARY

A draft standard entitled, "Standard for the Performance Testing of Extremity Dosimeters" (HPSSC P/N 13.32, June 1986) was prepared by a working group of the Health Physics Society Standing Committee (HPSSC) at the request of the Nuclear Regulatory Commission (NRC). This draft standard establishes the methods for testing dosimetry systems used to determine occupational radiation dose to the extremities. The draft standard also provides the performance criterion to be used to determine compliance of these systems. The final version of this HPSSC draft standard could be used to conduct performance testing of processors of extremity dosimeters. The performance testing could involve participation in a National Voluntary Laboratory Accreditation Program (NVLAP) similar to that used for whole body dosimeters. However, before the NRC would consider requiring accreditation of extremity dosimetry processors using the finalized standard, it is necessary to evaluate the appropriateness of the draft standard. Therefore, the NRC contracted with the Pacific Northwest Laboratory (PNL) to conduct a feasibility study to evaluate the draft standard as well as to obtain information regarding the performance of extremity dosimeters.

The study design was based on guidelines for the performance testing given in the draft standard. In the draft standard, seven irradiation categories are specified in which the performance may be tested. The irradiation categories include: low-energy photons (both general and accident dosimetry), high-energy photons (both general and accident dosimetry), beta particles, neutrons, and a mixture category. The draft standard proposes the following performance criterion to determine compliance: $|B| + S \leq 0.35$ (0.40 for ^{204}Tl) where B is the bias of the dosimeter measurements (calculated as the average of the performance quotients) and S is the standard deviation of the performance quotients.

PNL has conducted two separate evaluations of the performance of extremity dosimeter processors to determine the appropriateness of the draft standard, as well as to obtain information regarding the performance of extremity dosimeters. In 1986 and 1987, PNL conducted the initial evaluation. Twenty-one types of extremity dosimeters (both finger ring and wrist/ankle dosimeters) were received from 11 processor facilities. The study showed that approximately 60% of the time the dosimeter results met the performance criterion for accuracy and precision at the tolerance level specified in the draft standard.

Based on the results of the initial performance test, PNL investigated the sources of error through visits and telephone discussions with seven of the facilities that participated in the performance tests. The results of the investigation are summarized in this report. For two of the processors the major source of error was a result of inadequate procedures, or equipment malfunctions. Several of the processors indicated that they were not as well prepared for the performance test as they could have been, and that their performance would likely improve during subsequent tests.

Following the site visits and the discussions with the facilities participating in the performance test, a second performance test was conducted with the same 11 processor facilities that participated in the initial test and a total of 22 types of extremity dosimeters (several facilities submitted dosimeters for the second test that were designed differently than the dosimeters submitted for the first test). The results of the second performance test (summarized in this report) indicate that approximately 70% of the time for ring dosimeters and 81% of the time for wrist dosimeters the processors were able to meet the performance criterion at the tolerance level specified in the draft standard. This is an overall improvement of 15% to 18% from the results of the first performance test (comparing the results obtained using similar sources). However, the results also indicted that most processors were unable to meet the performance criterion consistently for all irradiation categories. For example, the best performances were in the accident categories, and the low-energy photon protection category for both ring and wrist dosimeters and also in the high-energy photon protection category for wrist dosimeters, with over 80% of the dosimeters in these categories passing at the performance criterion given in the draft standard. However, the worst performance was observed in the beta-particle category (for ring dosimeters) and the neutron category (for wrist dosimeters) with passing rates of 45% and 68%, respectively.

Variations were also observed in the results received from dosimeters irradiated by two different sources (or energy levels) within a single category. The most significant difference between sources was observed for ring dosimeters irradiated in the low-energy photon category (NIST filtered techniques H150 and M150) and in the beta-particle category (^{204}Tl and $^{90}Sr/^{90}Y$). For the wrist dosimeters, significant differences between sources (or energy levels) were observed in the low-energy photon category (NIST filtered techniques H150 and M150) and in the neutron category (moderated ^{252}Cf and unmoderated ^{252}Cf).

Based on the information obtained during the facility visits and the results obtained from the performance testing, it is recommended that changes be made ensure that to the draft standard is appropriate for extremity dosimeters. The changes include:

- subdividing the beta particle category thus providing the processors the opportunity to receive irradiations separately from the ^{204}Tl source or the $^{90}Sr/^{90}Y$ source,

- dividing the mixture category into two categories (the first corresponding to photon mixtures, and the second to mixtures of photons and beta particles), thus allowing the processors to participate in one type of mixture and not the other,

- eliminating the neutron category until appropriate flux-to-dose-equivalent conversion factors are derived,

- identifying to the processors the categories in which their dosimeters were irradiated (this recommendation is made in response to the inability of single chip ring dosimeters to discriminate between energies), and

- changing the tolerance level for the performance criterion to 0.30 for accident categories and 0.50 for protection categories to provide consistency with the performance criterion for whole body dosimeters (ANSI 1983) and to avoid making the draft standard overly difficult for extremity dosimeter processors to pass. Using the data obtained during this study, a tolerance level of 0.30 for accident categories and 0.50 for protection categories would have resulted in 81% of the ring dosimeters and 86% of the wrist dosimeters passing the performance criterion.

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GLOSSARY

absorbed dose (D) - The energy absorbed per unit mass in a material. The special unit of absorbed dose is the rad. The SI (International System) unit is the gray (Gy) [joule per kilogram (J/kg)]. 1 J/kg = 1 Gy = 100 rad.

accident dosimetry - Determination of high levels of absorbed dose resulting from unexpected conditions.

accuracy - the degree of agreement of a measurement with the true value. In this report the bias is used to ascertain the accuracy of the measurements.

bias (B) - The average of the performance quotients P_i, for n dosimeters, for a specified irradiation category and depth

$$B = \bar{P} = \frac{1}{n} \sum_{i=1}^{n} P_i$$

dose equivalent (H) - The product of the absorbed dose (D), the quality factor (Q), and any other modifying factors. The special unit of dose equivalent is the rem. When D is expressed in Gy, H is in Sieverts (Sv). 1 Sv = 100 rem.

dosimeter - A combination of absorbers and a radiation-sensitive element or elements packaged in a holder (the holder being considered as part of the dosimeter) that is used to provide a cumulative record of absorbed dose or dose equivalent received when worn by an individual.

exposure-to-dose-equivalent conversion factor for photons (C_X) - The numerical quantity that relates the exposure in air to the dose equivalent at a specified depth in a material of specified geometry and composition. The C_X factors are a function of photon energy, material geometry (e.g., cylinder, sphere, slab, or torso), and material composition (e.g., tissue equivalent plastic, soft tissue ignoring trace elements, or soft tissue including trace elements).

extremity - The current Code of Federal Regulations, 10 CFR 20, (CFR 1989) defines extremities as "hands and forearms; feet and ankles." In this report, extremities are defined as that portion of the arm extending from and including the elbow through the fingertips, and that portion of the leg extending from and including the knee and patella through the tips of the toes.

extremity dosimeter - A dosimeter designed to be worn on an extremity.

extremity dosimetry system - A system used to assess dose equivalent from external radiation to the extremities.

free-field dose equivalent - The dose equivalent assigned for neutron irradiation by assuming that the irradiation is performed in free space with no background from air and room scattering and no source asymmetry (Schwartz and Eisenhauer 1982).

irradiation category - Radiation type, energy, and dose levels for which the accreditation tests are performed.

performance criterion - Used to evaluate dosimeter performance. The formula is

$$| B | + S \leq L$$

where B is the bias, S is the standard deviation, and L is the tolerance level.

performance quotient (P_i) - The fraction difference between the reported and delivered absorbed dose or dose equivalent for the i^{th} dosimeter,

$$P_i = \frac{[X_i \text{ (reported)} - X_i \text{ (delivered)}]}{X_i \text{ (delivered)}}$$

where X_i (delivered) is the dose equivalent (H_S) or absorbed dose (D_S) assigned by the testing laboratory, and X_i (reported) is the corresponding dose equivalent (H_S) or absorbed dose (D_S) reported by the processor.

precision - The degree of conformity of repeated measurements to each other, whether or not they are accurate. In this report the standard deviation is used to ascertain the precision of the measurements.

processor - A supplier of personnel dosimetry services. These services include:

- furnishing dosimeters to the user,
- evaluating the readings of the dosimeters after their return in terms of shallow dose equivalent (or absorbed dose) as prescribed in the standard,
- documenting the results, and
- reporting the results to the user.

protection dosimetry - Determination of routine levels of dose equivalent for the purpose of controlling the dose equivalent received by radiation workers.

ring dosimeter - Any dosimeter worn on the fingers of the hand to measure radiation dose.

shallow absorbed dose (D_S) or dose equivalent (H_S) - The absorbed dose or dose equivalent to the depth of 0.007 cm in a material of specified geometry and composition.

standard deviation (S) - The standard deviation of the performance quotients, P_i, calculated for n dosimeters for a specified irradiation category and depth,

$$S = \sqrt{\frac{\sum_{i=1}^{n} (P_i - B)^2}{n - 1}}$$

test - Submission of dosimeters by a processor to a testing laboratory over a period of several months, in numbers sufficient for the specified irradiations in the test categories covered by the processor's service. A test includes:

- irradiation of the dosimeters by personnel of the testing laboratory using the type(s) of radiation specified for the test category,
- evaluation by the processor of the response of the returned dosimeters in terms of shallow dose equivalent for tests of protection monitoring or absorbed dose for tests of accident monitoring,
- submission of these evaluations to the testing laboratory,
- analysis of the submitted evaluations by the testing laboratory, and
- reporting of the results of this analysis (also referred to as "test results") to the processor.

testing laboratory - A group independent of the processor and authorized by the organization administrating the accreditation program to carry out the procedures specified in the standard.

tolerance level - The level of uncertainty in the dose equivalent that is used to evaluate dosimeter performance. The value of the tolerance level is defined in the draft standard.

wrist dosimeter - Any dosimeter worn on the wrist or ankle to measure radiation dose.

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INTRODUCTION

Radiation protection programs depend directly on correct measurement and quantification of radiation dose. Measurements should be as accurate and precise as possible for protection of the worker, as well as for use in any potential retrospective epidemiological studies. The quality of the measurements depend on several factors including the quality of the detector system and the quality of the calibration techniques. However, radiation measurements are subject to a variety of potential errors and uncertainties, including variations resulting from dosimeter manufacture, variations between dosimeter holder designs, uncertainties due to calibration techniques, errors and variations in reading equipment and techniques, variations in the angular response of dosimeters, and uncertainties resulting from the placement.

The importance of providing accurate personnel dosimetry processing to radiation workers led to a study performed by Battelle Northwest Laboratory [now called the Pacific Northwest Laboratory (PNL)] to determine a basis for film dosimeter performance criterion for whole body dosimeters (Unruh et al. 1967). Subsequently, in 1976 the U.S. Nuclear Regulatory Commission (NRC) contracted with PNL to conduct a study to compare and evaluate dosimetry processors against four existing standards (Nichols 1977). The study recommended adoption of a draft standard being developed by the Health Physics Society Standards Committee (HPSSC). Following performance testing studies, the standard was modified and published by the American National Standards Institute (ANSI) as ANSI N13.11-1983 "Personnel Dosimetry Performance - Criteria for Testing" (ANSI 1983). This standard provides a procedure for testing the performance of suppliers providing whole body dosimetry services to personnel who may potentially be exposed to ionizing radiation. In 1984, the NRC issued for comment a rule change (Federal Register 1984) to the Code of Federal Regulations that would require NRC licensees to use the services of dosimetry processors accredited under the National Voluntary Laboratory Accreditation Program (NVLAP) of the National Bureau of Standards (NBS) [now the National Institute of Standards and Technology (NIST)] for dose measurements required by the NRC. This action was initiated because performance evaluations of personnel dosimetry processors indicated that a significant percentage of such processors were not performing with a reasonable degree of accuracy. On February 13, 1987, the Commission approved a final amendment to 10 CFR 20 which requires NRC licensees to use accredited personnel dosimetry processors (Federal Register 1987). To be accredited, a processor is required to complete a NVLAP questionnaire and other application materials that involve documenting responsible personnel, equipment, facilities, and quality control procedures, to pass performance tests as described in ANSI N13.11-1983 and to pass onsite inspections by NVLAP assessors. ANSI N13.11 applies only to personnel whole body dosimeters whose readings are used to provide a lifetime cumulative personal irradiation record for an individual. Direct and indirect reading pocket ionization chambers and extremity dosimeters (those dosimeters used to measure the dose to hands and forearms, feet, and ankles) are not included in ANSI N13.11. The Commission has requested that the rule be applied to extremity dosimeters as soon as a suitable performance standard is available.

Although uniform standards governing the performance of extremity dosimetry systems do not yet exist, performance criterion for testing processors of extremity dosimeters are available in draft form. In March 1982, the NRC requested that the HPSSC form a working group to prepare a consensus standard defining performance and quality assurance criterion for extremity dosimeter processors. That working group prepared a draft standard, HPSSC P/N 13.32, "Standard for the Performance Testing of Extremity Dosimeters," which establishes the methods for testing dosimetry systems that determine occupational radiation dose to the extremities and the performance criterion for accuracy and precision that would be used to determine compliance. The draft standard also specifies the sources and energy ranges to be used during the performance testing as well as the irradiation geometries and extremity phantom designs. The final version of this HPSSC standard (as published by ANSI) could be used to conduct performance testing of processors of extremity dosimeters. The performance testing would involve participation in a NVLAP proficiency testing program similar to the program for whole body dosimeters.

The U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, contracted with PNL to determine the appropriateness of the draft standard for the performance testing of extremity dosimeters. Such a determination must be made before the NRC can consider requiring accreditation of processors using the standard as a performance criterion. Similar research projects involving the performance testing of personnel dosimetry services were conducted by the NRC (Plato and Hudson 1980; Plato and Miklos 1983) in support of ANSI N13.11-1983 (ANSI 1983).

In 1986 and 1987, Pacific Northwest Laboratory (PNL) conducted an evaluation of the draft standard (using Committee Draft V of the standard) and of the performance of extremity dosimeter processors to determine the appropriateness of the draft standard, as well as to obtain information regarding the performance of the extremity dosimeter processors. Twenty-one types of extremity dosimeters (both finger ring and wrist/ankle dosimeters) were received from 11 processor facilities. The dosimeters were irradiated by PNL to specific dose levels in one or more of seven categories specified in the draft standard and were returned to the processor facilities. The processors evaluated the doses and returned the results to PNL for analysis. The study, published as NUREG/CR-4959 (Harty, Reece, and Hooker 1987), showed that approximately 60% of the time the dosimeter results did not meet the performance criterion for accuracy and precision specified in the draft standard. Approximately two-thirds of the reported results exhibited large positive or negative biases (average of the relative biases of 15 dosimeters) ranging from 0.25 to 0.80 for the various test categories, and low standard deviations of the relative biases (less than 0.15). In addition the results appeared to be processor-dependent.

Based on the results of the initial performance test study (Study 1), PNL proposed to further investigate whether the draft standard would be appropriate for the performance testing of extremity dosimeters by identifying the sources of error in the performance of existing processors of extremity dosimeters and investigating in greater depth some of the assumptions used to develop the draft standard that appear to conflict with current

processing procedures. This report contains the results of the study to identify possible sources of error during the performance testing as well as the results of a second performance test (Study 2) that was conducted to quantify the amount of improvement.

The first section of this report presents the results of the visits made to the processor's facilities to identify the sources of error from the previous testing study. Information obtained from the visits includes a characterization of each of the facilities, a description of the dosimeter processing operations, the calibration procedures, personnel training procedures, and customer/operations communications. In addition, comments received from the processors on the test performance and the draft standard are given. The second section of this report describes the performance test design for Study 2, the facilities that participated in the study, procedures used for the performance study, and the results of the study. The procedures include a description of the dosimeter handling and irradiation, the dose equivalent calculation, and the test evaluation. A comparison is presented of the results of the current performance test and the results of the previous performance test (Harty, Reece, and Hooker 1987). Conclusions and recommendations for changes to the draft standard are given.

ERROR IDENTIFICATION STUDY

Site visits and telephone conversations were made following the 1987 performance study (Study 1) to determine the sources of error exhibited during the performance testing study as well as to answer questions that arose during the performance test. These contacts were also used to indicate the degree to which the assumptions made in the extremity draft standard pertain to current extremity dosimetry practices.

Site visits were made to six of the processor's facilities that participated in the previous study. In addition, detailed telephone conversations were held with one additional processor when scheduling problems precluded a planned site visit. The processors contacted included processors that demonstrated consistently good results during the previous performance testing study, processors that demonstrated consistently poor results, and processors that did not demonstrate consistent results.

The large amount of information obtained through the processor visits is categorized in the following discussion as follows: 1) facility characterization (including a description of the extremity dosimetry systems, the number of dosimeters processed, and the range of dose levels on the dosimeters), 2) dosimeter processing operations and procedures, 3) calibration of dosimeters, 4) training of processing personnel, and 5) customer/operations communications (including the dosimeter exchange rates and the extent to which processors are aware of the exposure sources in the workplace). Comments on the test performance study as obtained from processor contacts are also presented in this section.

FACILITY CHARACTERIZATION

Table 1 contains a description of the processors that were contacted during this study. Two of the processor's facilities were nuclear power utilities and one was an in-house facility that processes dosimeters from both medical and nonmedical sources. The remaining four facilities are large commercial processors of extremity dosimeters. The types of customers served by the commercial processor facilities are also listed in the table.

In order to better characterize the extremity dosimeter processors, Table 2 lists the dosimeter designs used by the processor that were contacted.(a) Table 3 indicates the number of dosimeters read during an average month and the dose ranges observed. Because this information is business-sensitive, some processors characterized the dosimeter volume in broad ranges. One processor contact did not have the information readily

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(a) The order of the information in each of the tables does not correspond directly to the order of information in any other table. In addition, the list of dosimeter types participating in this study is not organized by processor, but is presented in a list. This was done to ensure the anonymity of the facilities participating in this study.

TABLE 1. Facilities Contacted Following Initial Performance Test Study

Facility Type	Customer Types
Nuclear Power Utility	-
Nuclear Power Utility	-
Nuclear Medical Facility	-
Commercial Processor	Universities Veterinarians Industrial Fuel fabrication facilities Nuclear power plants X-ray diffraction user
Commercial Processor	Nuclear power utilities (constitutes majority of volume) Uranium fuel/resources Medical facilities Radiographers Others - including federal, research facilities, industrial, universities, product oriented companies and pharmaceutical companies
Commercial Processor	Medical facilities
Commercial Processor	Medical facilities Radiopharmaceutical companies Universities Research facilities

available; another (a commercial processor) was hesitant to provide any information regarding dosimeter volume.

DOSIMETER PROCESSING OPERATIONS AND PROCEDURES

Dosimeter processing operations and procedures include the process and equipment used to provide the initial pre-exposure screening, the reading, and the post-exposure evaluation of extremity dosimeters. All processors contacted indicated that they currently have established operational procedures. However, one processor indicated that their procedures had not been written until after the initial performance testing study; this processor exhibited consistently poor performance during the performance testing study.

The operations and procedures used to process extremity dosimeters varied from processor to processor. All of the processors screened the dosimeter phosphors after they initially received a new batch to ensure that the

TABLE 2. Dosimeter Types and Designs for Processors Contacted Following Initial Performance Test Study

1. Harshaw,(a) single-chip ring dosimeter
2. Harshaw,(a) single-chip, ring dosimeter
3. Harshaw,(a) single-chip, ring dosimeter
4. Harshaw,(a) single-chip, ring dosimeter;
5. Harshaw,(a) single-chip, ring dosimeter in plastic pouch
6. Panasonic,(b) 1-element ring dosimeter.
7. Harshaw,(a) single-chip, ring dosimeter in plastic ring
8. Panasonic,(b) 4-element, wrist dosimeter
9. Wrist film dosimeter
10. Harshaw,(a) 3-element, whole body dosimeter with elastic band for use as a wrist dosimeter;
11. Harshaw,(a) 4-element, combination wrist and albedo dosimeter
12. Film, wrist dosimeter

(a) Harshaw is a registered trademark of Harshaw/Fitrol Partnership, Solon, Ohio.
(b) Panasonic is a registered trademark of Panasonic, Inc., a division of Matsushita Electric Corporation of America, Secaucus, New Jersey.

phosphor's sensitivity falls within a desired range. However, two of the processors indicated that they screened only a fraction or sample of the dosimeters received. Their decision to accept or reject the entire batch of chips was based on the results obtained while screening the sample. No obvious correlations could be made between the methodology used to screen dosimeters and the results of the initial performance testing study.

Various methods were also used by the processors to correct for errors caused by variations between chip sensitivities or to ensure that the chip sensitivities remained within the range to which they were initially screened. One processor generated initial correction factors for the chips in each dosimeter and used these correction factors each time the dose was evaluated. Every two years, the chips were rechecked and new factors generated. Two processors generated a correction factor after each dosimeter was read by irradiating the dosimeter to a known dose and then re-reading the dosimeter. Neither of these processors annealed the dosimeters between the

TABLE 3. Volume of Dosimeters Processed and Ranges of Doses at Each Facility

Number of Dosimeters Read by Each Facility	Dose Range at Each Facility
300 to 400 ring dosimeters/month	Average 95 to 100 mrem
Information not given	Typically zero, although nuclear medical applications less than 100 mrem/month
Information not available	Less than 1 rem/year; no one is pushing the limit
1000 to 2000 wrist dosimeters/month 20 to 100 rings/month	90% record same dose as whole body All are less than 1 rem
> 50,000 rings/year	Wide range - majority below whole body dose (exception in nuclear medicine applications)
3500 dosimeters/month	Less than 1 R
500/year	Approximately 10 persons with dose over 5 rem/yr, although no one approaches limit for the skin. Most dosimeters show zero dose.

initial readout and the calibration readout, although they were annealed following the calibration readout. A fourth processor, which tested all phosphors upon initial receipt and accepted only those that gave results within a certain range, re-exposed the chips after reading the dose and then either accepted or discarded the chip depending on whether the sensitivity fell within the required range. A fifth processor used a similar process although only 8% to 10% of the dosimeters were checked on a random basis to ensure that their sensitivities were still within the appropriate range. A sixth processor checked to be sure that the dosimeters had been annealed properly by pulling a sample from the group of dosimeters that were returned each month and reading them. Aberrant chips were identified by this process. Although the seventh processor did not perform periodic acceptance testing of dosimeter phosphors, a fraction of the dosimeters were randomly chosen to be used as spikes and the performance of the spiked dosimeters was evaluated. At the time of the performance testing study, however, even this procedure was not used.

The type of reader used by each processor also varied. Three of the processors used automatic readers, and four used manually operated readers. None of the processors checked the glow curves at the time the dosimeters were read, although two processors recorded the glow curves using their equipment and save the data for referral as necessary. No correlation was

observed between the reader type and the performance test results, nor between the reading or recording of glow curves and the test results. Several processor representatives indicated that they wanted or were planning to read and/or save glow curves in the future, because this would give them an opportunity to reevaluate the dose after an abnormal reading.

Quality assurance checks of the equipment were performed by all processors including checks using calibrated dosimeters. However, in one processor's facility quality assurance checks using calibrated dosimeters were not performed during the previous testing period. This processor also exhibited consistently poor performance during the initial testing period, later noting that the problems were due to incorrectly operating reader equipment.

A comparison of the results of the previous test and the information provided by the processor suggests that good extremity dosimetry programs have established procedures for processing extremity dosimeters, and use calibrated dosimeters to provide quality assurance checks on instruments used to read dosimeters. Of the two processors that showed consistently poor performance during the performance testing, one had no written procedures at the time of the test, and the other had equipment problems that went undetected because the processor did not make routine quality assurance checks of their equipment (using dosimeters irradiated with a known dose) to ensure that the equipment was working correctly.

CALIBRATIONS

During the previous performance test (Harty, Reece, and Hooker 1987), much of the failure rate appeared to be the result of the bias. For this reason, one of the areas investigated in this study involved the type of calibration sources that were used by the processors during the previous performance test. Table 4 lists the calibration sources for each of the processors. Six of the seven processors used ^{137}Cs as a calibration source. One processor, however, used ^{60}Co. Two of the processors also performed calibrations for neutrons, one using moderated ^{252}Cf and the other using a plutonium-beryllium source. In addition, the latter processor also used a beta source owned by another firm.

Although the processor that calibrated to ^{60}Co exhibited poor performance during the study, it appeared most likely that the poor results were from factors in addition to, or other than, the calibration source. No distinct relationship between the calibration methods and the results of the performance test was observed for the other processors.

TABLE 4. Calibration Sources Used by the Processors Contacted Following the Initial Performance Test Study

1. ^{137}Cs for photons and beta particles
   ^{252}Cf for neutrons
2. ^{137}Cs
3. ^{137}Cs
   Plutonium-beryllium source for neutrons
   Other facility owned source for beta
4. ^{137}Cs
5. ^{60}Co for both gamma and neutron
6. ^{137}Cs
7. ^{137}Cs

TRAINING OF PERSONNEL

The training of processing personnel varied from processor to processor. All seven processors had some on-the-job training; however, two of the processors stressed classroom training in addition to on-the-job training. One processor, which exhibited very good performance during the previous study, attributed much of their success to their comprehensive training program and the respect given to their technical support staff. A second processor with good performance indicated that they designed their systems to prevent employees from making mistakes in areas in which mistakes were commonly made; thus, they stressed on-the-job training. One processor expressed concern that the technician responsible for reading the dosimeters during the previous performance testing study may have been too technically oriented for such a routine job and thus a source of some of the error.

CUSTOMER/PROCESSOR COMMUNICATIONS

In addition to operations and training, the communication between the dosimeter processors and the dosimeter users was investigated. Although this relationship did not influence the results of the performance testing, it does affect assumptions made in the draft standard. Two specific areas requiring close communication were identified: 1) knowledge of the exposure sources for the dosimeters and 2) dosimeter exchange rate and variability in dose rates among the dosimeters worn by a given individual during a year.

The proper interpretation of dosimetry results requires the knowledge of the radiation fields in the exposure environment. Thus, accurate results are only possible if the type of radiation and its energy spectrum is known or is able to be determined from the response of the dosimeter. Single chip

dosimeters calibrated to ^{137}Cs, for example, can underrespond significantly to low-energy photons and betas (Reece et al. 1985). Because the variation in response to sources in different categories is in many cases significantly greater than the 30% uncertainty goal allowed in the draft standard, processors of single chip dosimeters frequently find that the identification of the energy spectrum from the exposure source is necessary before the dose can be determined.

In-house communication of the source of exposure seemed to be good, with the processors having a knowledge of the sources that irradiated the dosimeters and conditions in which they are used. This is largely because for in-house processing facilities, the dosimeter users are part of the same organization as the dosimeter processors. However, communication between commercial processors and their customers varied. According to one facility, much of the variation was due to varying levels in customers' understanding of radiation and dosimetry. According to this facility, although they notify customers of the calibration sources they are using and explain that they have correction factors for various types of radiation, some customers do not ask for the correction factors. However, some of the customers (for example the power plants) appeared to be applying their own correction factors after they received the data. Another processing facility encouraged customers to provide the energy spectra in their workplace and indicated that they would measure the spectra at the customer's request. Other processors explained to their customers their need for energy spectra information, but left it up to the customer to provide information about the energy at which a dosimeter had been irradiated. One processor pointed out that ultimately the licensee (the customer) is responsible for requesting and applying the correction factors.

Another area of customer/processor communications is the frequency of dosimeter exchanges that is requested by the customer. The draft standard assumed a quarterly exchange rate and approximately uniform doses on each of the four dosimeters worn by the same individual in a year in the calculation of the performance criterion to be used for comparison against the test results. Five processors exchanged dosimeters primarily on a monthly basis, although they indicated that infrequently exchanges may occur on either a per-job basis, weekly, biweekly, or quarterly, depending on the customers preference. One processor exchanged dosimeters every 6 weeks. In another processor facility 90% of the dosimeters were exchanged on a per-job basis; when the job was completed the dosimeter was read and new dosimeters were issued for the next job.

COMMENTS ON TEST PERFORMANCE

The processor contacts were asked the reasons for their success or failure during the performance tests. For one processor, good performance results were credited to the training and the respect they paid to their personnel and, in turn, the personnel's attention to quality. Another processor gave credit to their participation in NVLAP, and the development and attention paid to their extremity dosimetry program.

According to responses from several processors, negative results were from not having "geared up" for this study, or from processing the test dosimeters "on the side," rather than using the technicians or automated equipment used for processing their regular dosimeters, thus, introducing the possibility of clerical errors. Two processors that exhibited consistently poor responses in the previous performance tests were able to identify specific problems occurring during the testing. In one of the facilities, there were no procedures manuals or quality assurance manuals in place at the time of the performance tests (although this situation has since changed). In addition, the readers were not working well during the test period and the personnel in charge of the dosimetry program was changing. In the other processor's facility, the problem was largely due to their reader equipment although the lack of quality assurance dosimeters processed at that time was also a contributing factor. This processor had not been using quality assurance dosimeters at the time of the study, and its staff did not realize that there were equipment problems, which they later attributed to poor contact between the heater and the phosphor.

The consensus of the processors at the facilities visited was that during the initial performance testing study the facilities were not as prepared as they could have been and, if the test were run again, the results would improve. Two processors indicated that their performance had improved with each successive test during early tests for NVLAP, and that they expected the same trend during the extremity dosimeter performance testing.

COMMENTS ON THE DRAFT STANDARD

Personnel responsible for the extremity dosimetry programs at each of the processor's facilities visited following the initial performance testing study were asked to comment on the draft standard. The comments received, which are given in Appendix A, encompass the performance criterion, the categories included in the draft standard, the variation in sources within the categories, and the terminology used in the draft standard.

PERFORMANCE TEST

Based on the results of the processor visits and the input of the processors contacted, the performance testing was rerun to quantify the amount of improvement over the preceding test. Descriptions of the test design, the study participants, the procedures, and the results of this second performance test (Study 2) are provided below.

TEST DESIGN

The test design for the second performance test study was similar to that used during the initial performance test study (Harty, Reece, and Hooker 1987) and was based largely on the performance test design given in Committee Draft VIII (April 1988) of HPSSC the draft standard. The draft standard specified seven irradiation categories in which processors that process extremity dosimeters may receive accreditation. The irradiation categories specified in the draft standard appear in Table 5 along with the sources specified for each category and the energy and dose ranges for each category. The categories include both accident dosimetry (doses to 10 to 500 rad) and occupational (protection) dosimetry (dose equivalents of 0.25 to 20 rem).(a) The categories include high-energy and low-energy photons, beta particles, neutrons, and mixtures. A nearly monoenergetic, low-energy photon source (Category IIIB) and uranium slab sources (Category VB) were included for application to specific occupational environments. These categories were included for use in place of, or in addition to, Categories IIIA and VA, respectively, depending on the occupational environment covered by the dosimetry service.

During an accreditation program, processors of extremity dosimeters would select the irradiation categories for which they desire accreditation from the list in Table 5. The processors would then send the dosimeters required for the tests to the testing laboratory; the test dosimeters would be submitted in three separate groups of five dosimeters for each of the categories selected. The testing laboratory would irradiate each group of dosimeters in turn and return them to the processors before the next group of dosimeters is sent. The doses would be evaluated by the processors and then submitted to the testing laboratory, where the test results would be evaluated against specific performance criterion. At the completion of all three rounds of testing, the results would be reported to the participating processor facilities.

(a) The test range for Category VA was changed from a range of 0.25 to 20 rem to a range of 0.15 to 10 rem for purposes of the performance test, because of the length of time required to irradiate dosimeters with the sources included in this category.

TABLE 5. Irradiation Categories

Category		Energy	Test Range
I.	Low-Energy Photons (X Ray)-Accident Dosimetry		10 to 500 rad
	NIST Filtered Technique		
	M150	70 keV (average)	
II.	High-Energy Photons-Accident Dosimetry		10 to 500 rad
	^{137}Cs	662 keV	
IIIA.	Low-Energy Photons (X Ray)-General		0.25 to 20 rem
	NIST Filtered Techniques		
	M30	20 keV (average)	
	S60	36 keV (average)	
	M150	70 keV (average)	
	H150	120 keV (effective)	
IIIB.	Low-Energy Photons (X Ray)-Plutonium Environments		0.25 to 20 rem
	Monoenergetic	15 to 20 keV	
	Monoenergetic	55 to 65 keV	
	^{241}Am	59 keV	
IV.	High-Energy Photons		0.25 to 20 rem
	^{137}Cs	662 keV	
VA.	Beta Particles - General		0.15 to 10 rem
	^{204}Tl(a)	0.76 MeV (maximum)	
	$^{90}Sr/^{90}Y$ (filtered)	2.3 MeV (maximum)	
VB.	Beta Particles - Slab Uranium		0.25 to 20 rem
	Natural Uranium	2.3 MeV (maximum)	
	Depleted Uranium	2.3 MeV (maximum)	
VI.	Neutron		0.25 to 20 rem
	^{252}Cf (moderated)(b)		
	^{252}Cf (unmoderated)		
VII.	Mixture Categories		0.25 to 20 rem
	III. & IV.		
	III. & V.	} one energy from each category	
	IV. & V.		
	III. & VI.(c)		
	IV. & VI.		

(a) A modified performance algorithm is recommended.
(b) Moderated by 15 cm of D_2O (Schwartz and Eisenhauer 1980).
(c) For work environments containing plutonium, use the monoenergetic or ^{241}Am sources.

DESCRIPTION OF PARTICIPATING FACILITIES

The eleven processors that participated in Study 1 were contacted to determine their interest in participating in the second study. All eleven processors chose to participate. The processors include six dosimeter processor vendors, four electric utility companies, and a medical research laboratory. A list of the irradiation categories was sent to each of the processors, and they chose the categories in which they wished to participate and the type of dosimeter (ring or wrist) they would submit. Several processors submitted more than one type of dosimeter. One processor (Processor C) was not routinely using their ring dosimeters with low-energy photons or beta particles. Thus, their performance in Categories IIIA, VA, and VII might not reflect their ability to pass an accreditation test.

A total of 22 types of extremity dosimeters, including 11 types of ring dosimeters and 11 types of wrist dosimeters, were included in this study. Several processor had changed their dosimetry programs and were using a different type of dosimeter than they had used during the first performance test study. Thus, the dosimeters submitted for the first study were not necessarily the same as those submitted for this study. Ten of the ring dosimeters contained a single thermoluminescent (TL) element; one ring dosimeter contained two TL elements. Two of the wrist dosimeters were film dosimeters; the remaining wrist dosimeters were multi-element TL dosimeters.

PROCEDURES

This section describes the specific dosimeter handling and irradiation procedures, the dose equivalent calculation procedures, and the test evaluation procedures used in this study. Changes from those procedures used during the first study are noted.

Dosimeter Handling and Irradiation Procedures

The second performance study was conducted in two rounds, rather than the three rounds specified in the draft standard, due to time constraints and because the purpose of this second study was to quantify the amount of improvement over the previous performance test study rather than to actually accredit processors. For each round, the participating processors shipped one group of five dosimeters for each of the categories in which they were participating. Eight to 10 extra dosimeters were sent with each shipment for each type of dosimeter, to be used as controls and spares. Upon receipt, the dosimeters were counted, logged in, assigned a specific identification number, and organized into groups for irradiation. Dosimeters awaiting irradiation or shipment were stored together in an area of low-background radiation dose. The control dosimeters remained in the low-background storage area while the irradiations were performed.

As specified in the draft standard, the dosimeters were irradiated on phantoms except for those exposed to the uranium source. The uranium exposures were performed by placing the dosimeters directly upon the uranium slab. Two phantom types were specified by the draft standard: one to represent a

finger to test ring or hand dosimeters, and one to represent a lower arm or leg to test wrist or ankle dosimeters. The finger phantom was a right circular cylinder constructed of methylmethacrylate with a diameter of 19 mm (0.75 in.) and a length of 610 mm (24 in.). Two arm phantom designs were used: one for neutron exposure and one for photon and beta exposures. The arm phantom for the neutron exposures was a right circular cylinder made of solid methylmethacrylate. The neutron arm phantom had a diameter of 73 mm (2.9 in.) and was 610 mm (24 in.) in length. The arm phantom for the photon and beta exposures was constructed of a methylmethacrylate outer cylinder with an aluminum inner cylinder. The aluminum insert for the arm phantom used for photon and beta exposures was 60 mm (2.4 in.) in diameter and was nested inside the methylmethacrylate tube, which had an inner diameter of 60 mm (2.4 in.) and an outer diameter of 73 mm (2.9 in.). The tubes were of the same length and were 457 mm (18 in.) long. The phantom designs were researched in a study as reported by Roberson, Eichner, and Reece (1986).

Irradiations on the finger phantom were performed in sets of five dosimeters where possible; irradiations on the wrist phantom were performed in sets of three dosimeters where possible. The order of the dosimeters on the phantom was alternated each time, and no two dosimeters from the same processor were irradiated together. Thus, a suspected misirradiation could be checked by comparing dosimeter results from other processors. An exception occurred for Processor J, during Round 1, where the Round 1 dosimeters were resubmitted and irradiated individually (one dosimeter per phantom) as a result of an earlier confusion between the testing laboratory and the processor on the appropriate orientation of the dosimeters on the phantom.

The sources specified by the draft standard for each of the categories are listed in Table 5. The draft standard specifies that for each category, except for the category specifically identified as that dealing with radiation mixtures (Category VII), only one type of radiation and one energy spectrum are to be used for all three rounds of a given test. However, for this study, the source used in the multiple-source categories was varied so that the study would identify changes in response to the different sources. The specific source used in each round of the test was randomly selected for each category from the list in Table 5 with the exception of the ^{241}Am source, which was not available for Category IIIB, and the depleted uranium slab, which was the only source available for Category VB. The random selection occurred without replacement for categories containing two or more sources. Thus, the same source was selected only once. Two of the processors participating in Category VII specified that their dosimeters not be included in specific mixtures. For these processors, a second selection of sources was made during Round 2.

The method specified in the draft standard (Committee Draft V, June 1986) for the selection of irradiation levels was suggested by ANSI N13.11-1983 (ANSI 1983). This process involves the selection of random numbers, ρ, uniformly distributed between 0 and 1. The logarithm of the dose equivalent, H, is then calculated as:

$$\log H = \log(H)_l + \rho[\log(H)_u - \log(H)_l] \quad (1)$$

where $(H)_l$ and $(H)_u$ are the lower and upper limits, respectively, of the test irradiation levels in question. The random selection of the logarithms of the irradiation levels rather than of the levels themselves increases the probability of selecting values near the lower limit of the range.

For collimated beams, the phantom was positioned so that the central beam axis was perpendicular to and passing through the center of the phantom. For uncollimated beams, the center of the phantom was perpendicular to the radial line from the source center. The calculation of the dose took into account the variation in radiation intensity at the position of each dosimeter on the phantom.

Pretest calibration exposures were provided for the neutron category. Also provided was the ratio of a 23-cm (9-in.) diameter spherical rem meter and a 7.6 cm (3-in.) diameter sphere covered with 0.03-cm (0.010-in.) thick cadmium to provide a relative calibration for albedo dosimeters (Griffith et al. 1979). This ratio is 2.70 for unmoderated ^{252}Cf and 0.31 for the moderated ^{252}Cf [moderated by 15 cm (5.9 in.) of D_2O as reported by Schwartz and Eisenhauer (1980)].

The processors participating in Categories I, II, and VI (the accident categories and the neutron category) were given the opportunity to assign dosimeters to these categories before the dosimeters were sent to the testing laboratory. The dosimeters in the remaining categories were chosen at random by the testing laboratory. Thus, the specific dosimeters irradiated in Categories I, II, and VI were known by the processors when the dosimeters were returned for evaluation. However, the remaining dosimeters were packaged together so that the processor would not know which dosimeters were irradiated in Categories III, IV, V, or VII. This was done in response to a previous draft of the standard that indicated that processors should not know the identification of dosimeters irradiated in Categories III, IV, V, and VII. After receiving the dosimeters, the processors read them and reported the dose to the testing laboratory. After the results were received by the testing laboratory, a letter was sent to each of the processors, listing the identification number for each dosimeter that was irradiated in Categories III, IV, V, and VII and requesting that the processors reanalyze their results based on this information. The source and the irradiation level used were not identified for any of the categories except for Category VI, for which the source (moderated versus unmoderated ^{252}Cf) was specified. Following receipt of the final Round 2 results, a letter was sent to the processors providing them with the results of the Round 1 irradiations and requesting that they reevaluate the Round 2 results based on this information. Thus, the Round 1 results could be used as a calibration for Round 2.

Dose Equivalent Calculation Procedures

The dose equivalent assigned to dosimeters exposed to photons was calculated using the exposure-to-dose-equivalent conversion factors (C_x), developed in a study jointly supported by the NRC and the DOE (Roberson, Eichner, and Reece 1986) and shown in Table 6. The shallow dose equivalent

TABLE 6. Exposure-to-Dose Equivalent Conversion Factors (C_X) for Extremity Phantoms at Shallow Dose (Roberson, Eichner, and Reece 1986)

	Conversion Factors (C_X), rad/R	
	Arm/Leg Phantom	Finger Phantom
Filtered X-Ray Techniques		
M30	0.99	0.95
S60	1.05	0.99
M150	1.14	1.01
H150	1.13	1.02
K-Fluorescence X-Ray Techniques by Energy, keV		
16	0.96	0.92
23	1.00	0.96
31	1.03	0.98
40	1.06	0.99
59	1.13	1.00
75	1.14	1.01
98	1.15	1.02
Gamma Ray Sources		
^{137}Cs	1.02	0.98
^{60}Co	1.00	0.98

(H_S) or absorbed dose (D_S) for the photon irradiations using a sealed source, was calculated as

$$H_S = Q\, C_X\, \dot{X}_{air}\, t \qquad (2a)$$

or

$$D_S = C_X\, \dot{X}_{air}\, t \qquad (2b)$$

where Q = the quality factor, defined as 1.0 rem/rad (assumed for calculation of dose to the extremities, although not defined for the extremities)

C_X = the exposure-to-dose-equivalent conversion factor for shallow dose(s) for the extremity phantom

$\dot{X}_{air}$ = exposure rate in air

t = irradiation time

For x-ray exposures referenced to an unsealed monitor ionization chamber, the shallow dose equivalent (H_S) or absorbed dose (D_S) was calculated as

$$H_S = Q\ C_X\ T\ M\ C_{TP} \tag{3a}$$

or

$$D_S = C_X\ T\ M\ C_{TP} \tag{3b}$$

where Q and C_X are as defined above

T = the exposure-per-charge calibration factor for the monitor chamber at the standard temperature and pressure

M = the reading of the monitor chamber in units of charge

C_{TP} = the temperature and pressure correction factor for the monitor chamber

The shallow dose equivalent assigned to dosimeters exposed to beta-particle fields was calculated using the equation:

$$H_S = \dot{D}_t(d)\ t\ Q\ C_{trans} \tag{4}$$

where $\dot{D}_t(d)$ = the absorbed dose rate at the calibration depth d

t = the time,

Q = the quality factor, defined as 1 rem/rad (assumed for the calculation of dose to the extremities although not defined for the extremities)

C_{trans} = the transmission factor defined as

$$C_{trans} = \frac{\dot{X}\ (7\ mg/cm\ )^2}{\dot{X}(d)} \tag{5}$$

where $\dot{X}$ is the relative extrapolation chamber signal, corrected for temperature and pressure and d is the original calibration depth.

Calculation of the free-field dose equivalent for dosimeters exposed to the unmoderated ^{252}Cf source was based on the following formula (Schwartz and Eisenhauer 1982):

$$H_d = \frac{N\ C_{UN}\ t\ (3600)}{4\pi r^2} \tag{6}$$

where H_d = the deep dose equivalent in a torso phantom (assumed to be equal to the shallow dose equivalent in an extremity phantom)

N = the neutron emission rate (n/sec)

C_{UN} = the deep dose-equivalent conversion factor for unmoderated ^{252}Cf (3.33×10^{-5} mrem/cm^2/n)

t = the time in hours

3600 = the number of seconds in an hour

r = the calibration distance (from the source center to the front surface of the phantom, cm)

For the moderated source, the following formula (Schwartz and Eisenhauer 1982) was used:

$$H_d = \frac{N\, C_M\, t\, (3600)(0.885)}{4\pi r^2} \qquad (7)$$

where C_M = the deep dose-equivalent conversion factor for moderated ^{252}Cf (9.08×10^{-6} mrem-cm^2/n)

0.885 = a factor that allows for the loss of the number of neutrons moderated below the cadmium cutoff as a result of the cadmium surrounding the D_2O sphere

and N, t, r, and the factor, 3600, are as defined above.

The current flux-to-dose-equivalent conversion factors as specified in regulations and recommendations of the National Council on Radiation Protection and Measurements (NCRP 1971) are derived from the maximum value of dose equivalent in a 30-cm- (11.8-in.-) diameter cylindrical torso phantom. These values include secondary charged particles from neutron interactions as well as contributions from gamma rays from the absorption of neutrons by hydrogen atoms. Although the cylindrical torso phantom model is not applicable for the extremities, the flux-to-dose equivalent rate conversion factors recommended by the NCRP (1971) were applied in this study in the absence of more pertinent information.

Typical values for the photon component ^{252}Cf are 7% of the neutron dose equivalent for unmoderated irradiations (Plato and Hudson 1980) and 18% for moderated irradiations (McDonald et al. 1983). These values were verified for PNL's irradiation facilities using neutron sources calibrated directly to NIST sources and the values were supplied to the processors. Because pre-test calibrations were given, corrections were not applied to the neutron dosimeter readings for scattering.

The radiation sources used in this study were calibrated directly or indirectly to NIST sources. The uncertainty in the assigned dose equivalent was calculated as given in Appendix B. The calculated uncertainty did not exceed 5% (excluding uncertainties in the dose-equivalent conversion factors

and in the photon component of the neutron irradiations).[a] The calculated uncertainty includes the following: the uncertainty in the source standardization, the uncertainty in positioning the dosimeter, the uncertainty in timing the exposure, and the uncertainty due to scattered radiations. The random uncertainties (positioning of the dosimeter, timing of the exposure, and source calibration) are summed quadratically. The ±5% limit applies to the linear sum of systematic uncertainties and one standard deviation calculated for the random uncertainties.

Dose-rate uniformity measurements were performed with the phantoms in place to determine the useful exposure area for each source. Position-dependent correction factors were used to comply with the uncertainty limits.

Test Evaluation Procedures

The dosimeter performance was evaluated using the following performance criterion specified in the draft standard:

$$| B | + S \leq L \tag{8}$$

where B = the bias
S = the standard deviation
L = the tolerance level.

This performance criterion was used for the test evaluations in order to be consistent with the draft standard. A similar performance criterion was specified in ANSI N13.11-1983 (ANSI 1983).

The performance quotient, P_i, is a measure of how close the reported or measured dose is to the true or delivered dose:

$$P_i = \frac{[X_i \text{ (reported)} - X_i \text{ (delivered)}]}{X_i \text{ (delivered)}} \tag{9}$$

where X_i is the absorbed dose or dose equivalent. The performance quotient can also be termed the relative bias.

The bias, B, is the average of the performance quotients, P_i (or an average of the relative biases), of the dosimeters tested:

$$B = \bar{P} = \frac{1}{n} \sum_{i=1}^{n} P_i \tag{10}$$

The bias provides an estimate of the accuracy of the dosimeters (how close the reported dose is to the delivered dose).

(a) The values used for the C_X factors and for the photon component of the neutron irradiations were provided to the processors.

The standard deviation, S, is a measure of the precision of the performance quotients or, in other words, of how closely the performance quotients (relative biases) are grouped together:

$$S = \sqrt{\frac{\sum_{i=1}^{n} (P_i - B)^2}{n - 1}} \qquad (11)$$

The standard of performance, i.e., the tolerance level, was based upon recommendations in the International Commission on Radiation Units and Measurements (ICRU) Report 20 (ICRU 1971) and in NCRP Report 57 (NCRP 1978). These reports recommend a 30% limit on the uncertainty of the dose equivalent in the vicinity of maximum permissible dose (MPD). For extremities (defined as "hands and forearms; feet and ankles"), the maximum permissible dose is given in 10 CFR 20 (CFR 1989) as 18-3/4 rem per calendar quarter (75 rem/yr). At one-quarter of the MPD, the NCRP allows as acceptable, a lower level of accuracy (e.g., a factor of 2). The ICRU suggests a factor of 3 on the uncertainty for doses of one-tenth the MPD. At higher doses, such as may occur during accidents, an accuracy of ±20% was considered appropriate by the NCRP. Early drafts of ANSI N13.11 included different performance criterion for various levels of dose. However, performance tests of whole-body dosimeters indicated that this was unnecessary over the typical range of dose equivalents (ANSI 1983). The tolerance level in the draft standard was adopted to approximately represents the requirement that the annual assignment of dose equivalent should be within 30% of the conventionally true value for 95% of the personnel receiving in excess of one-tenth of the maximum permissible dose equivalent. The derivation of the tolerance level assumed a dosimeter exchange rate of four times per year and approximately uniform occupational exposures.

Because of the uncertainty in the assigned dose equivalent (which did not exceed ±5%, excluding uncertainties in the dose-equivalent conversion factors and the photon component of the neutron irradiations), the performance criterion adopted in the draft standard was set to:

$$|B| + S \leq 0.35 \qquad (12)$$

Because of technical and practical limitations of current dosimeter designs, the test for the low-energy beta source (^{204}Tl) listed in Table 1 was set to:

$$|B| + S \leq 0.40 \qquad (13)$$

A discussion of the appropriateness of the performance criterion is given later.

RESULTS

The results of the second performance test study are reported and are compared to the results of the initial performance test (as reported in Harty, Reece, and Hooker 1987).

Current Test Results

The average of the biases (B) and the standard deviation (S) were calculated for each model of dosimeter submitted for testing in each of the categories. The calculations were performed separately for each round of testing (five dosimeters per round in each category) in order to compare the results obtained in each round. The sum of the absolute value of the bias and the standard deviation was calculated for each round to compare against the tolerance level of 0.35 (0.40 for ^{204}Tl) designated by the draft standard for the performance criterion.

Appendix C contains the performance data for each type of dosimeter tested in this study. Appendix C is organized by irradiation category. The processor codes and dosimeter model codes are provided. Appendix C lists the irradiation source, the bias (B), standard deviation (S), and the sum of the absolute value of the bias and the standard deviation ($|B| + S$) for each round of testing.

The results of the dosimeter performance are plotted in Figure 1 (bias), Figure 2 (standard deviation), and Figure 3 ($|B| + S$) for ring dosimeters and in Figure 4 (bias), Figure 5 (standard deviation), and Figure 6 ($|B| + S$) for wrist dosimeters. The radiation sources used in each round for each category are identified along the x-axis. The data points are coded A through K to correspond to each of the 11 processors. A second lower case letter beside the processor code indicates the dosimeter model for facilities that submitted multiple dosimeter models. The dashed line in Figures 3 and 6, placed at 0.35, represents the tolerance level specified in the draft standard. A second dashed line in Figures 3 and 6, placed at 0.40 above the ^{204}Tl label, represents the tolerance level for the low-energy beta source (^{204}Tl) used in Category VA.

Data points that are off-scale in the positive direction are identified above each of the graphs. For the ring dosimeters submitted by Processor A, the off-scale performance in Categories II and IV appeared to result from assigning the dose read on a given dosimeter to one of the other dosimeters irradiated in the group. Reassigning the doses in each category results in a performance index of less than 0.1 for both Categories II and IV. The same problem occurred for wrist dosimeters from Processor K in Category I, and from Processor H (wrist dosimeter H1) in Category IV. The reason for the off-scale results from other facilities was not readily apparent.

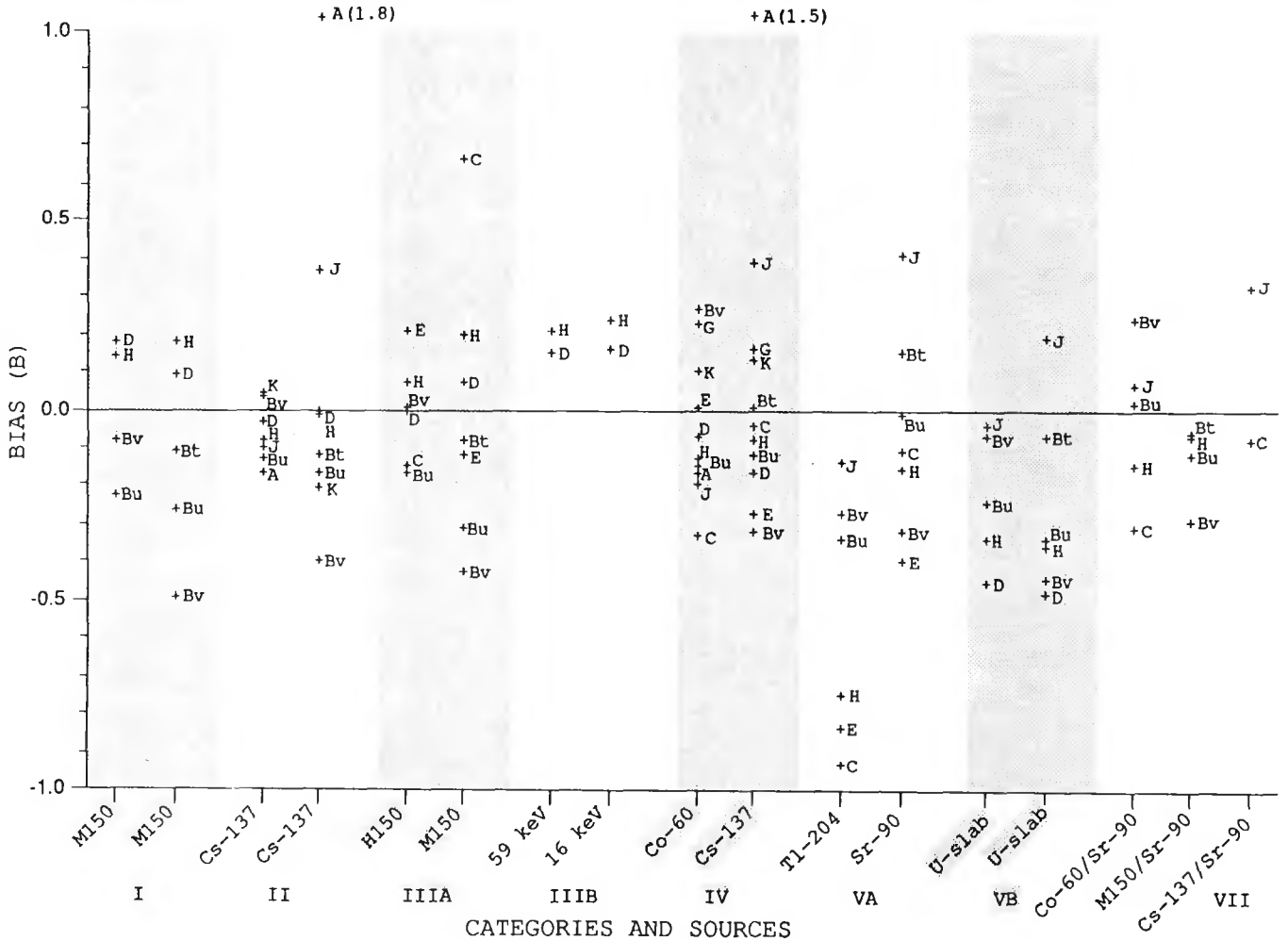

FIGURE 1. Summary of Performance - Bias (Ring Dosimeters)

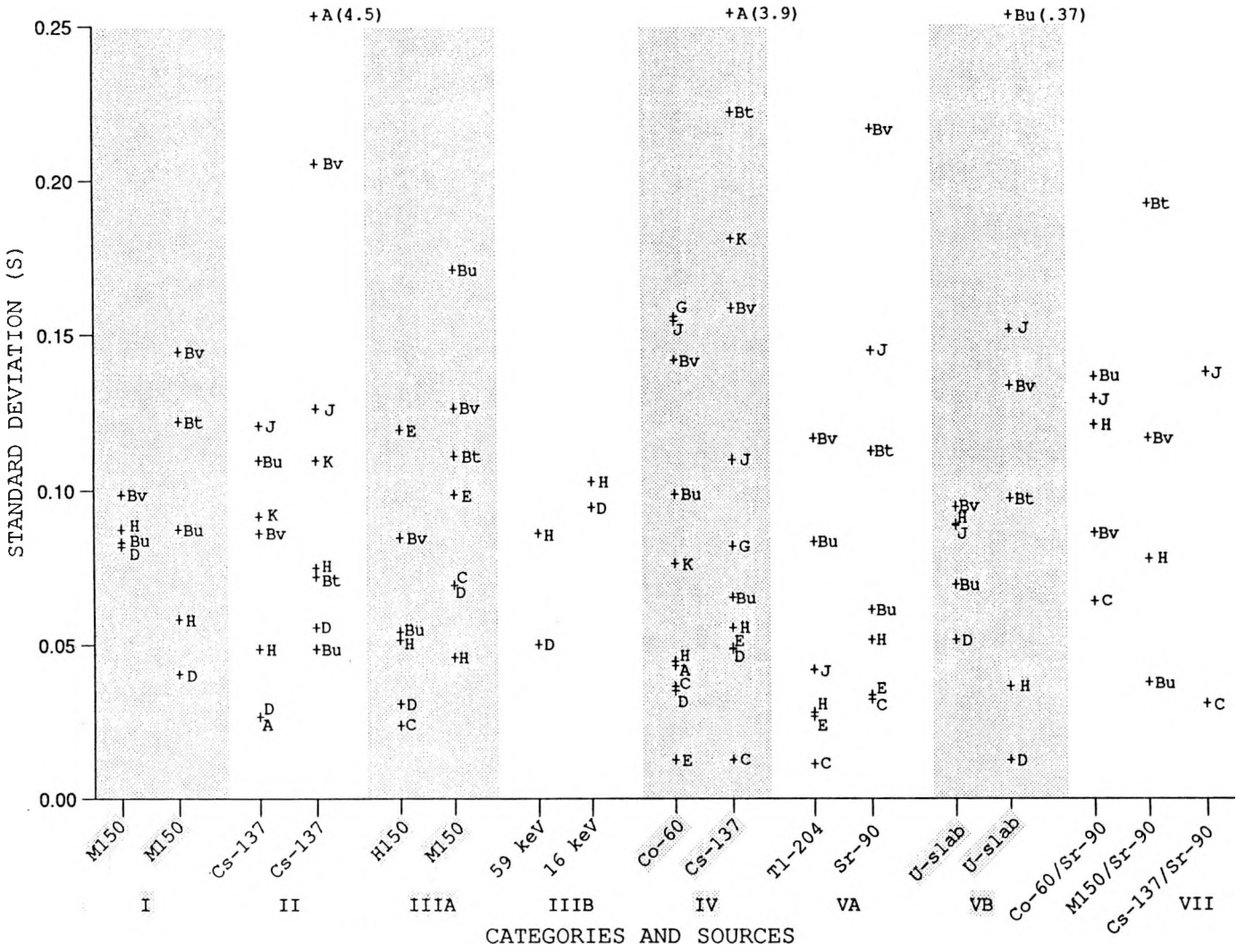

FIGURE 2. Summary of Performance - Standard Deviation (Ring Dosimeters)

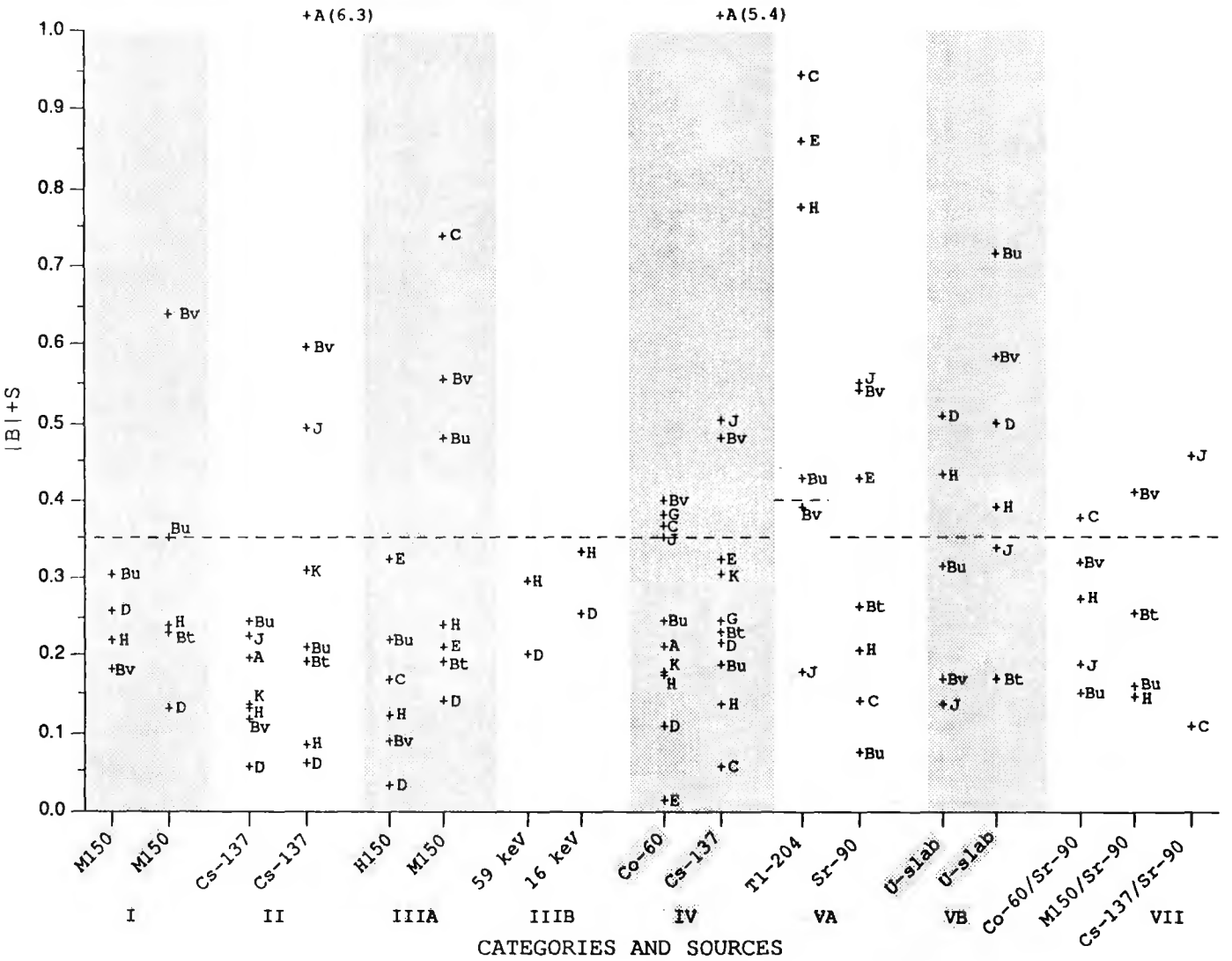

FIGURE 3. Summary of Performance - | B | + S (Ring Dosimeters)

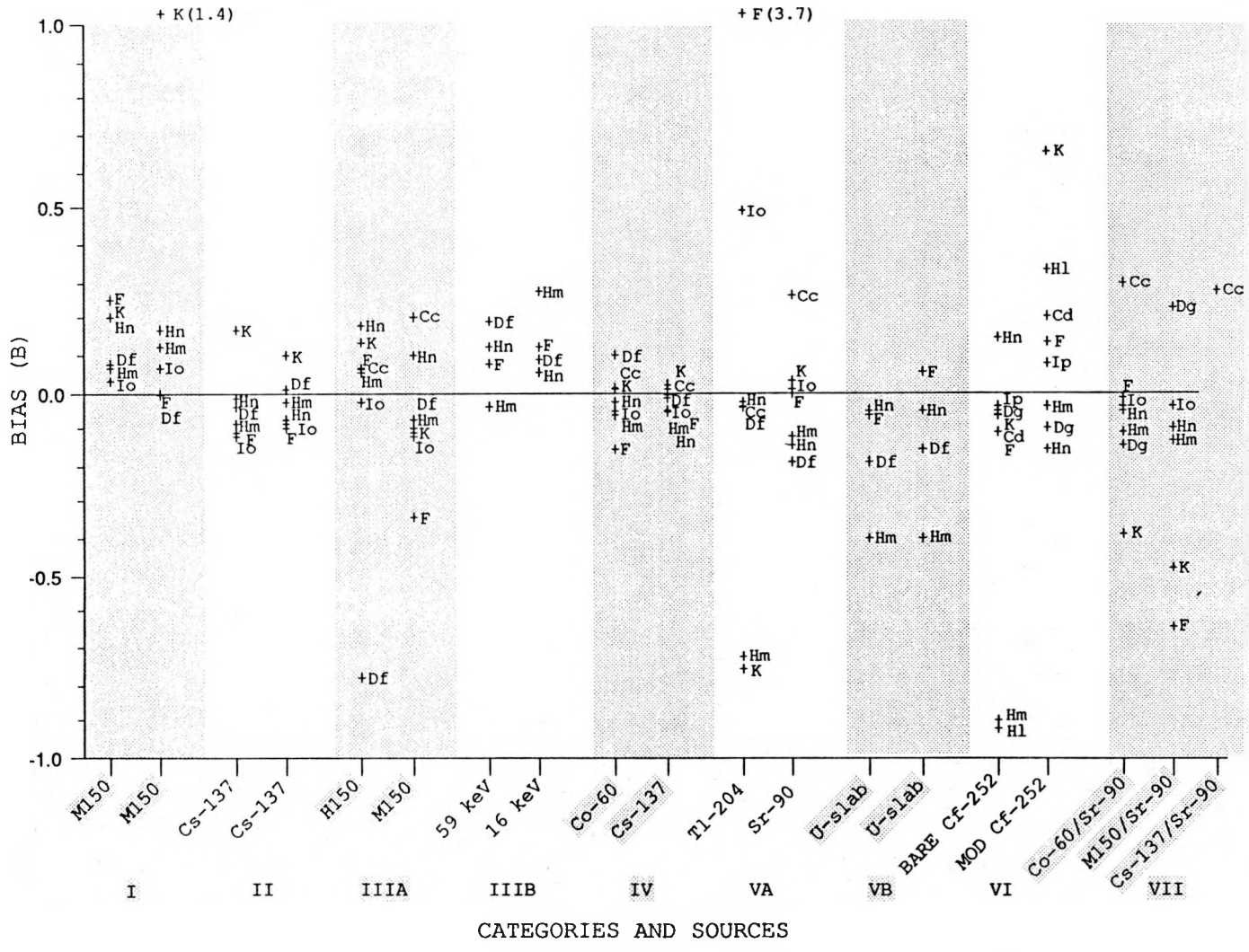

FIGURE 4. Summary of Performance - Bias (Wrist Dosimeters)

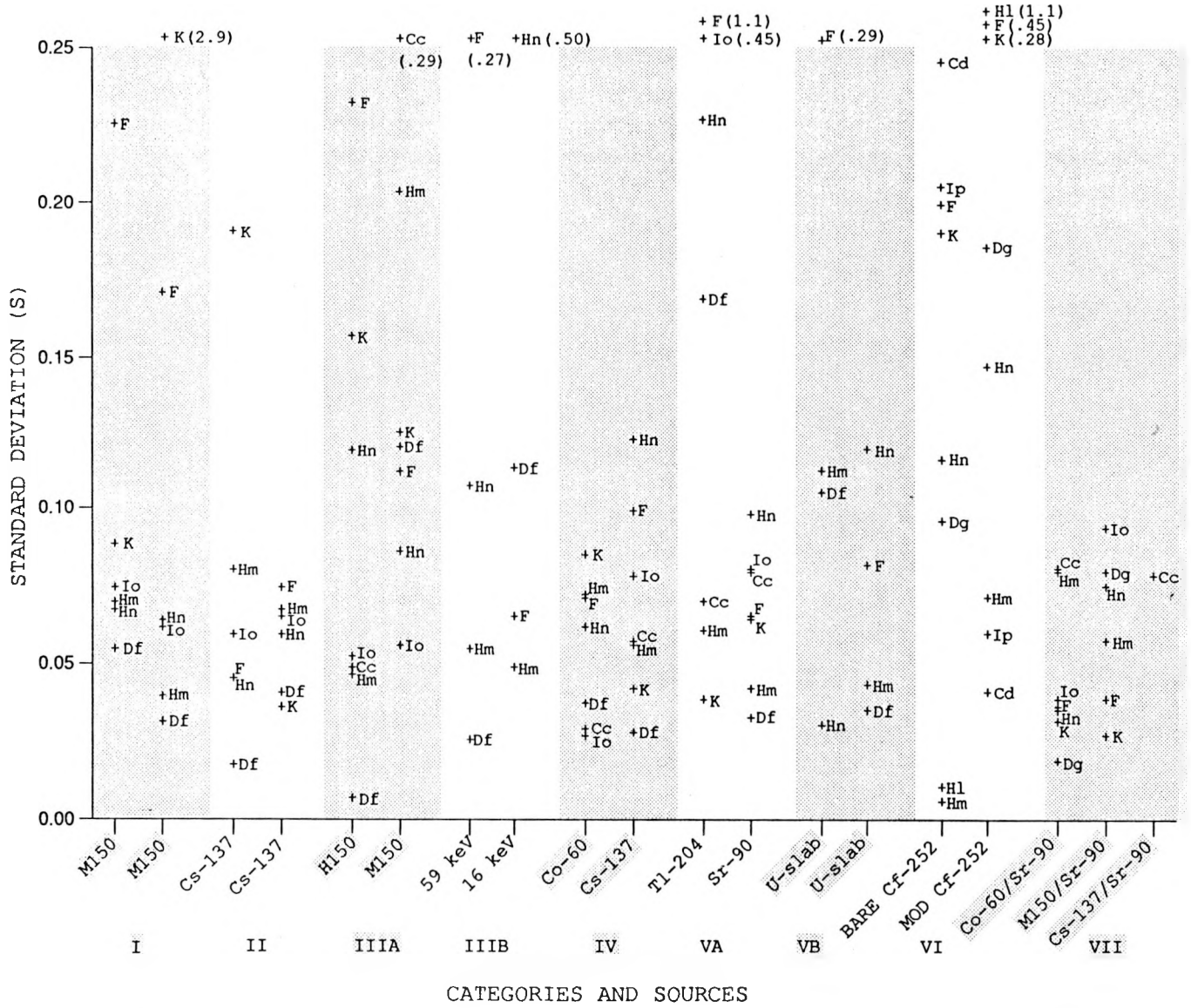

FIGURE 5. Summary of Performance - Standard Deviation (Wrist Dosimeters)

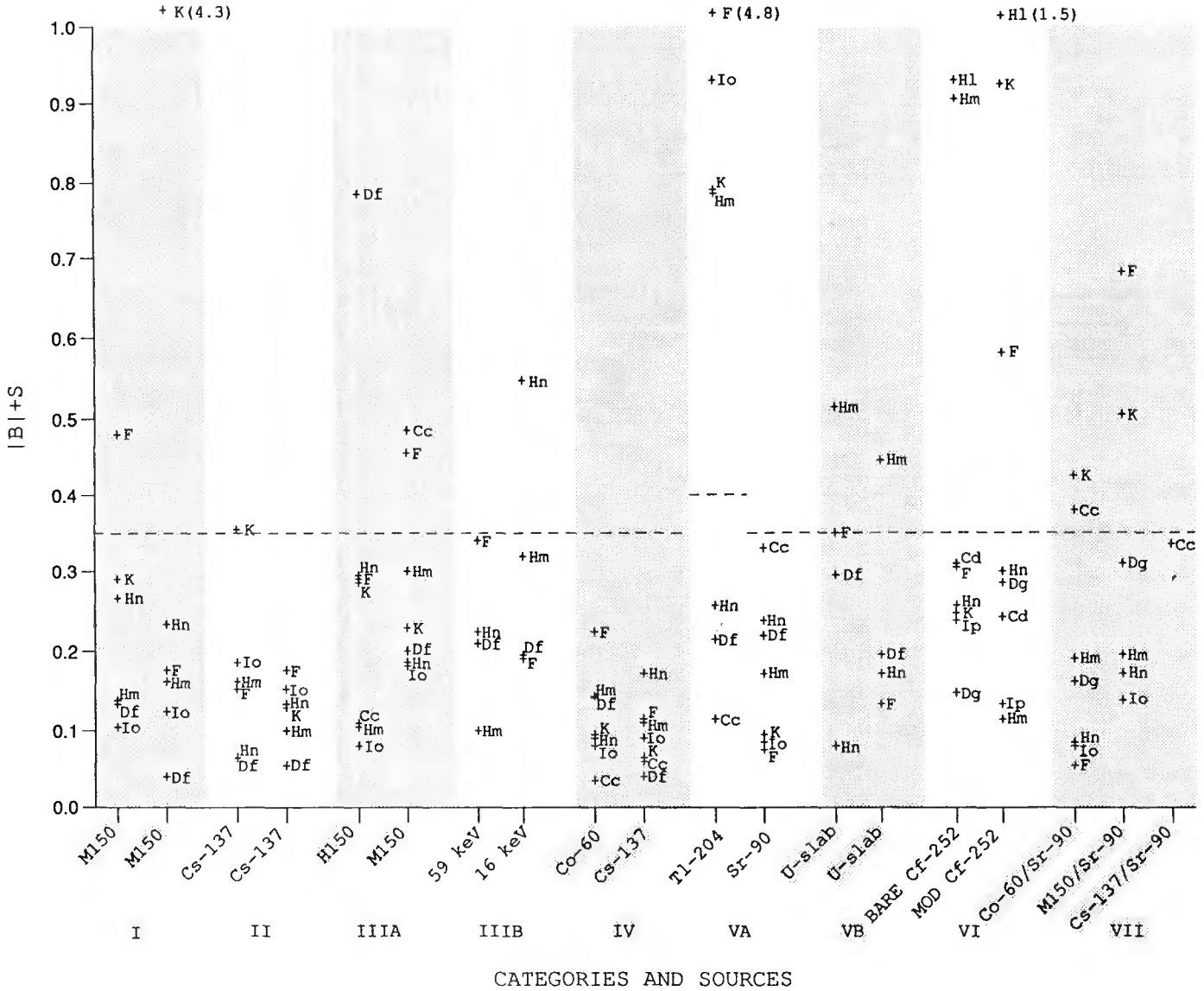

FIGURE 6. Summary of Performance - | B | + S (Wrist Dosimeters)

For the ring dosimeters, the best performances[a] were exhibited in Categories I (low-energy photons), II (high-energy photons), and IIIB (low-energy photons-plutonium environments) with the dosimeters in each of these categories passing the test at the 0.35 tolerance level over 80% of the time. The worst performances were observed in Categories VA (beta particles, general) and VB (beta particles, slab uranium) in which the dosimeters passed only 46% and 45% of the time, respectively. There was some variation in the results within categories, based on the source that was used for the irradiations. The performance quotients [calculated in Equation (9)] were used to determine the amount of variation between sources (or energy levels) used for the multiple-source Categories IIIA, IIIB, IV, VA, and VII. A test of the variances in these categories (using an F-test at the 95% confidence level) showed a significant difference for the variances obtained from Category IIIA using the two NIST filtered techniques (H150 and M150). The difference between the means of the performance quotients was found to be statistically significant only in Category VA (for ^{204}Tl and $^{90}Sr/^{90}Y$) using Student's t-test at the 95% confidence level.

For the wrist dosimeters, the best performances were exhibited in the accident dosimetry Categories I (low-energy photons) and II (high-energy photons), and the protection Categories IIIB (low-energy photons - plutonium environment), and IV (high-energy photons) with over 80% of the dosimeters passing the test at the 0.35 tolerance level. The worst performance was observed in Category VI (neutrons) with only 68% of the dosimeters passing at the 0.35 tolerance level. The wrist dosimeters also showed some within-category variation between sources (or energy levels). A test of the variances in the performance quotients using an F-test at the 95% confidence level showed a significant difference between the variances only in Category IIIA (for the two NIST techniques H150 and M150) and in Category VA (for the sources ^{204}Tl and $^{90}Sr/^{90}Y$). The difference between the means of the performance quotients was found to be statistically significant only for Category VI (moderated ^{252}Cf and unmoderated ^{252}Cf) using Student's t-test at the 95% confidence level.

The results are clearly processor dependent. For ring dosimeters, three of the processors passed in over 80% of the categories they were tested in and four processors passed in 60% or less of the categories they were tested in. For wrist dosimeters, four of the processors passed in 80% or more of the categories they were tested in, and one processor passed in less than 60% of the categories they were tested in.

The results given for finger rings in Figures 1 and 2 indicate that the major cause of not passing the performance test was the bias rather than the standard deviation. For ring dosimeters, the average standard deviation is 0.09, while the average bias (calculated as the average of the absolute value of each bias) is 0.21. Figures 4 and 5 show that for wrist dosimeters the cause of failure was somewhat evenly divided between the bias and standard

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(a) The results given in this report are based on an analysis of the dosimeter performance on a per round basis rather than combining the results for both rounds.

deviation, with an average standard deviation of 0.11 and an average bias (calculated as the average of the absolute value of each bias) of 0.16.

Overall, 70% of the time the ring dosimeters passed and 81% of the time the wrist dosimeters passed at the tolerance level given in the draft standard. The more successful passing rate for the wrist dosimeters was expected because the wrist dosimeters submitted for the performance test were multi-element dosimeters, which are better able to discriminate between energies than single-element dosimeters. The ring dosimeters, with one exception, are single-element dosimeters. However, the performance of the dual-element ring dosimeter was not consistently better than the single-element ring dosimeters.

Following the initial analysis of the dose for each round of testing, the facilities were notified of which dosimeters were irradiated in Categories III, IV, V and VII and asked to reevaluate the dose on the dosimeters in these categories (the dosimeters irradiated in Categories I, II and VI were identified to the facilities when the dosimeters were returned from the testing laboratory). Figures 7 and 8 show the initial results (+) compared to the reevaluated results (0). Most facilities did not take the opportunity to change their results. When changes were made, the changes were not necessarily an improvement. Overall, the results for both the ring and wrist dosimeters improved by only 1%. This is due in part to not identifying to the processor the source that was used. Thus, the processor did not have any information regarding the irradiation source for those dosimeters irradiated in multiple-source categories.

Following submittal of the final results for Round 2, processors were provided with a list of the doses delivered to each of the dosimeters during Round 1 and a list of the sources used during Rounds 1 and 2. The facilities were then asked to use this information to reevaluate the dose received by the Round 2 dosimeters. Again, only a fraction of the facilities altered their results based on this information. Overall, the results improved by only 2% for ring dosimeters over the initially obtained results. The performance of the wrist dosimeters, however, was decreased by 3% following disclosure of the results.

Comparison with Results of Previous Test

A comparison of the results from the previous study conducted in 1987 (Study 1) and the current study (Study 2) is shown graphically in Figures 9 and 10 for ring and wrist dosimeters, respectively. For purposes of comparison, the results were calculated on a per round basis for each category, rather than combining the results for the three rounds in Study 1 or the two rounds in Study 2 for each of the categories. Figures 9 and 10 compare the results from similar sources used in the studies rather than including all the results obtained in both performance test studies.

The results indicate an overall improvement: from 55% passing for the rings and 63% passing for the wrist dosimeters during the 1987 study, to 70% passing for the rings and 81% passing for the wrist dosimeters during the current study. Although these figures indicate that the improvement in the

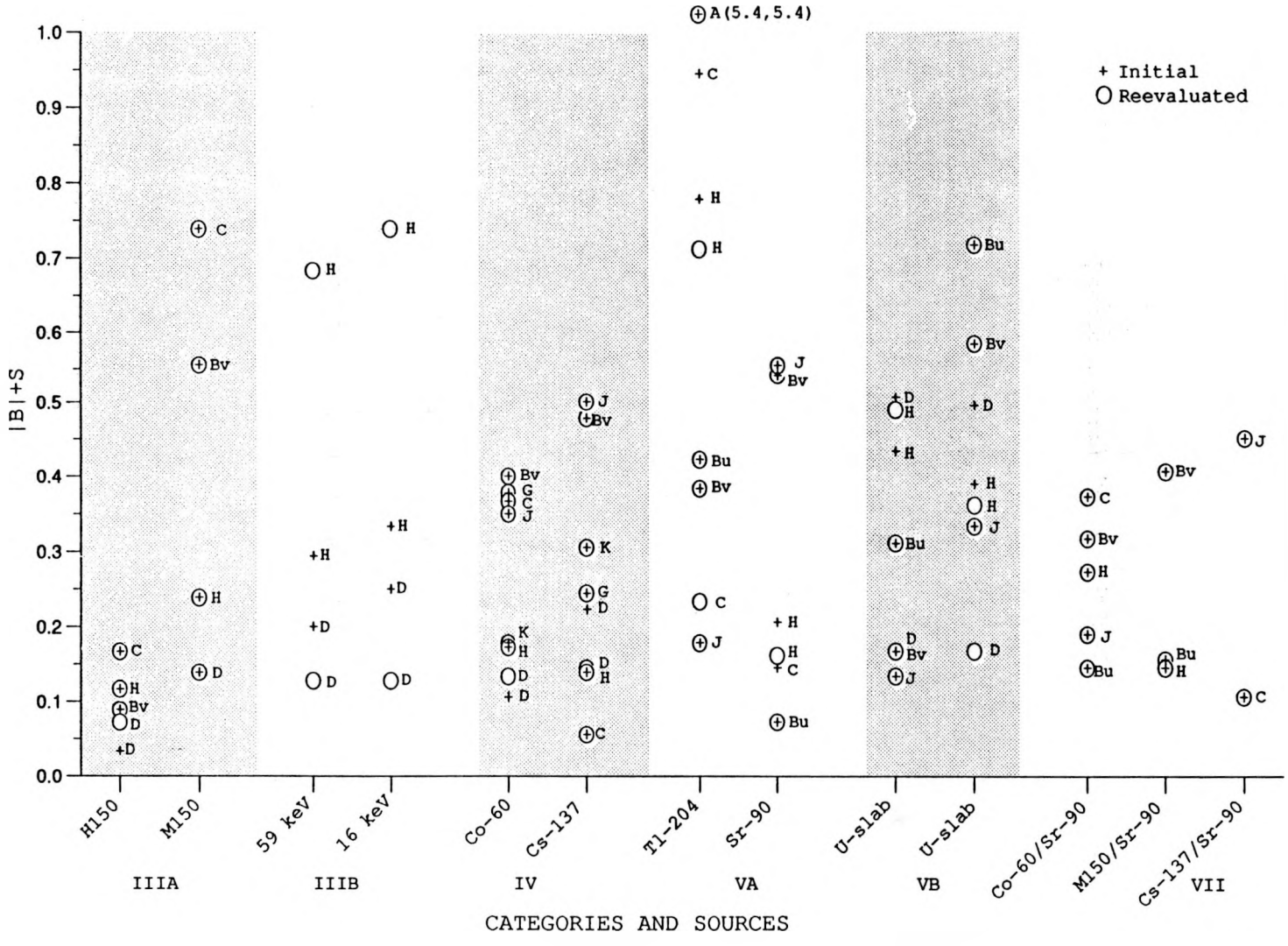

FIGURE 7. A Comparison of the Initial and Reevaluated Doses (Ring Dosimeters)

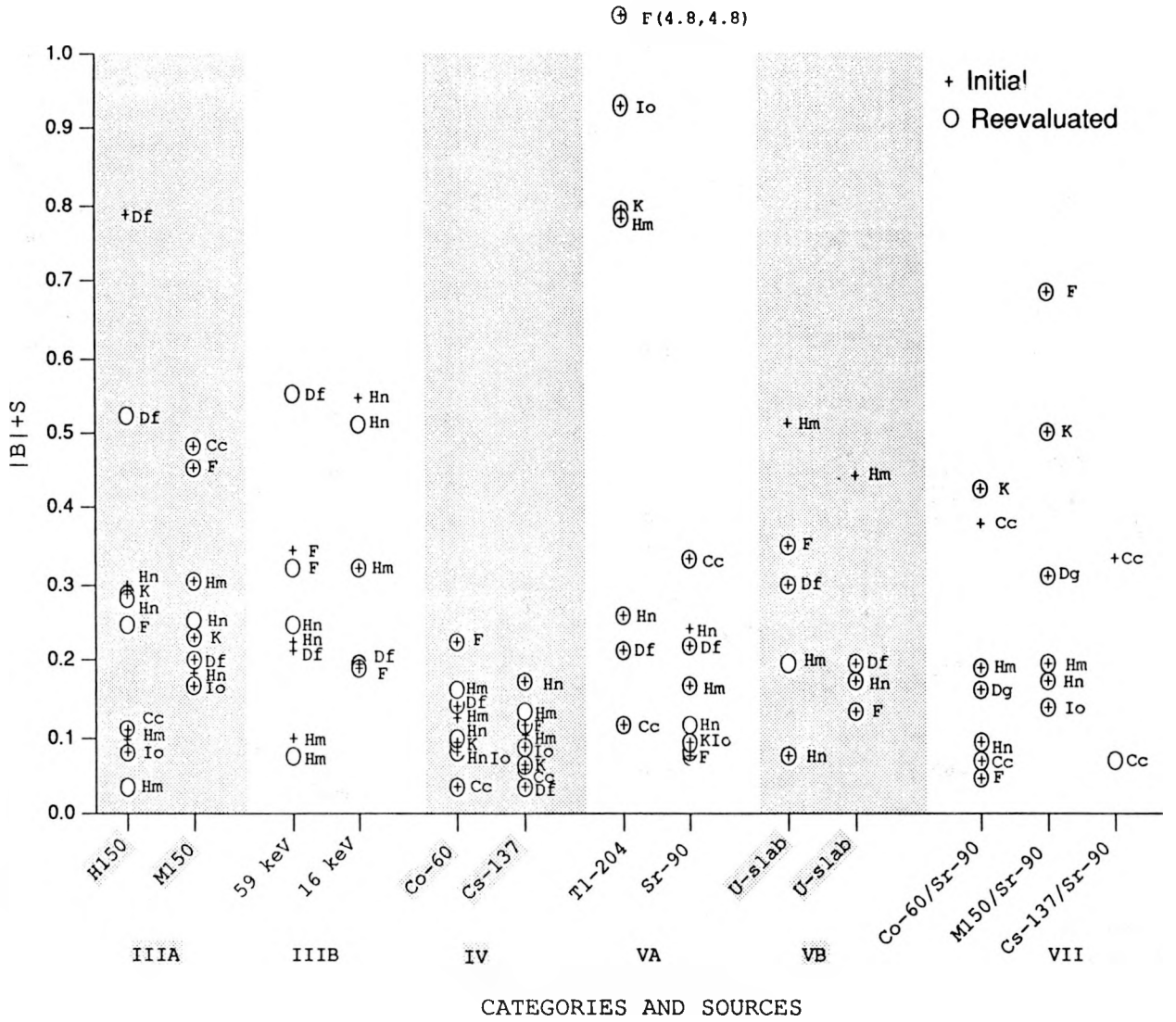

FIGURE 8. A Comparison of the Initial and Reevaluated Doses (Wrist Dosimeters)

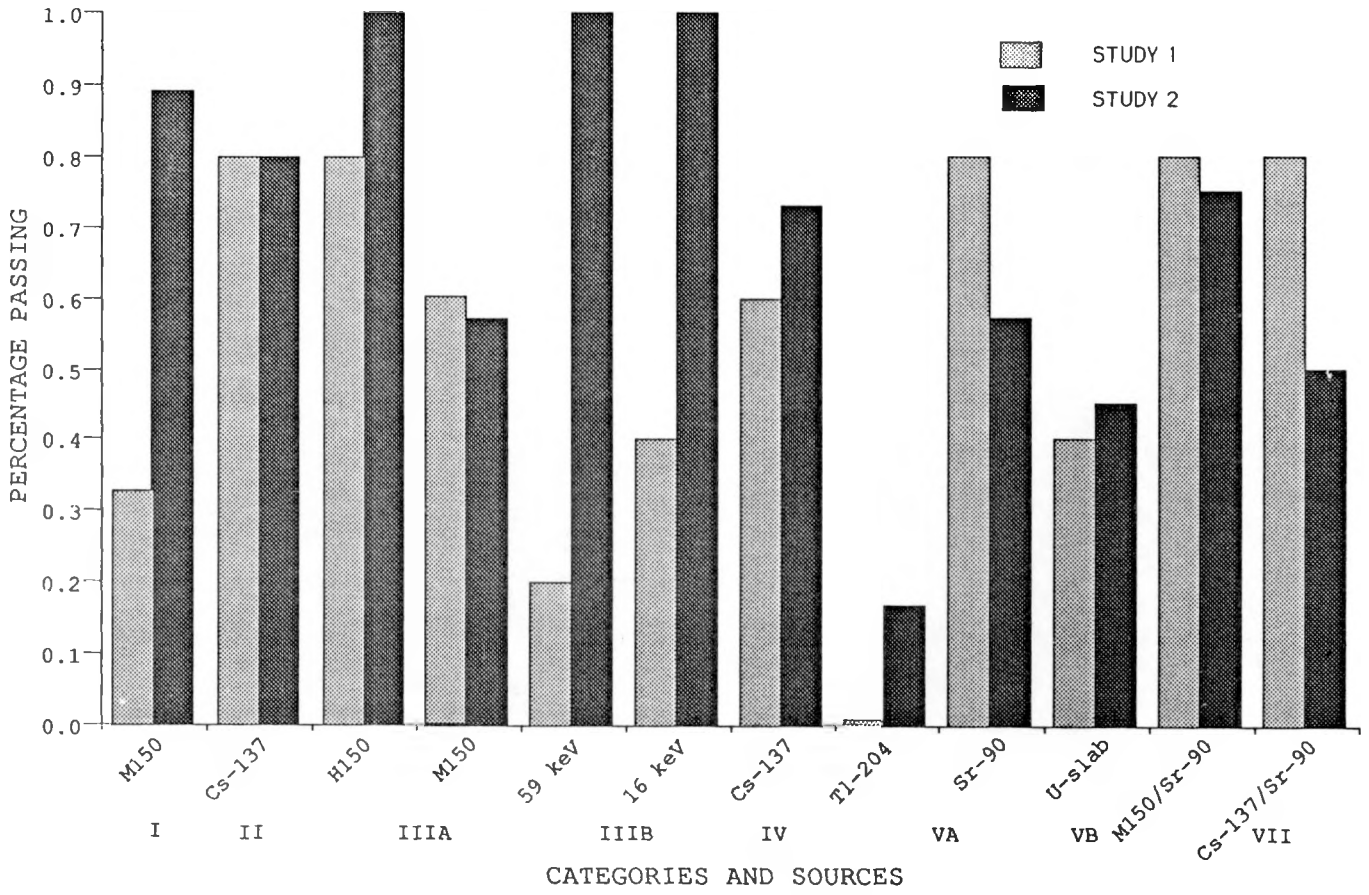

FIGURE 9. A Comparison of the Study 1 Results with the Results from Study 2 (Ring Dosimeters)

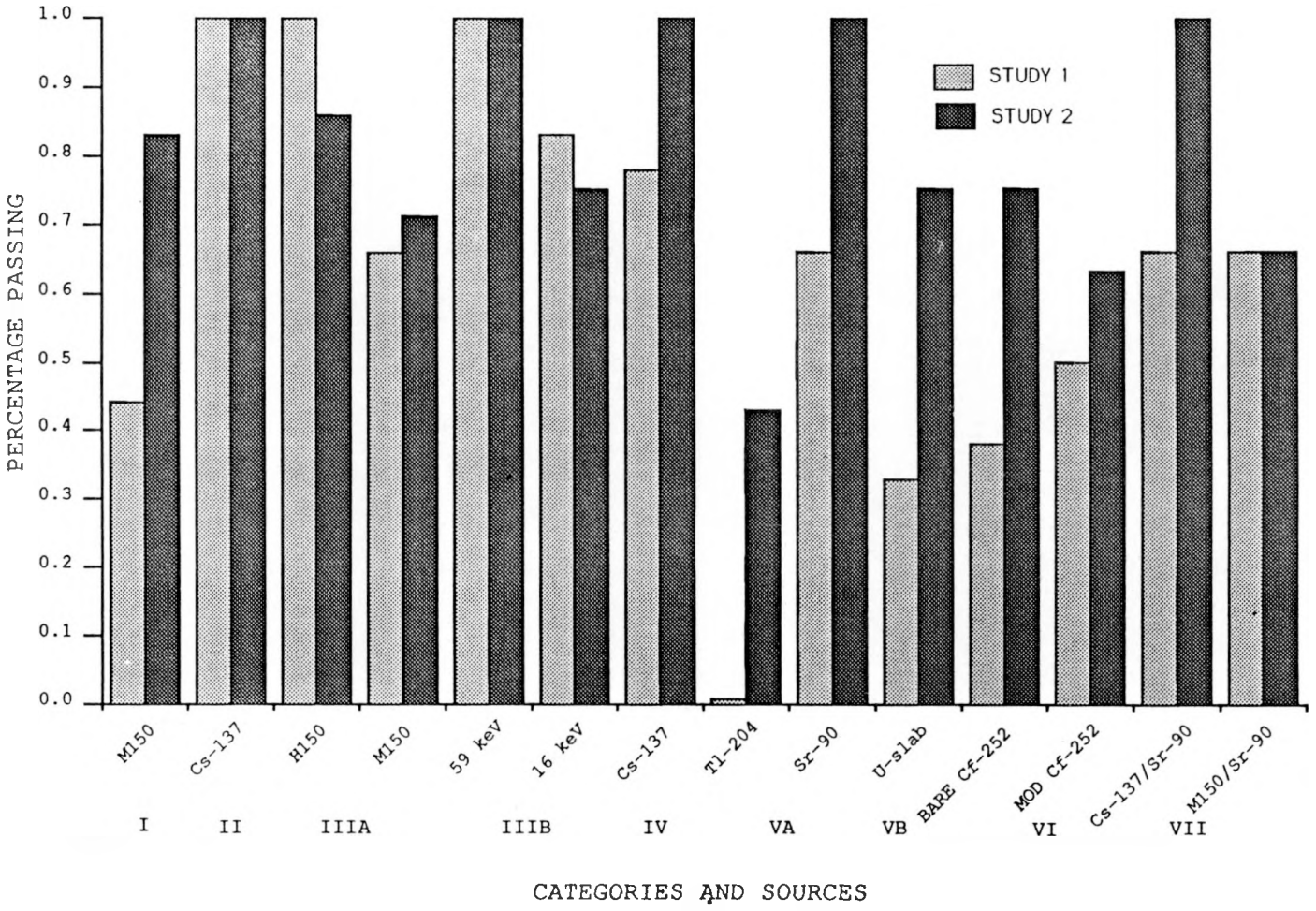

FIGURE 10. A Comparison of the Study 1 Results with the Results from Study 2 (Wrist Dosimeters)

passing rate has been between 15% and 18%, the dosimeters used in each category during the first study are not necessarily the same ones used during the second study, as some processors changed dosimeter types, while others entered additional or different categories than they had during the first set of tests. However, the results do indicate an improvement in the overall program for the facilities participating in the study.

APPROPRIATENESS OF THE DRAFT STANDARD

Before the draft standard can be used to conduct performance testing of extremity dosimeter processors, the standard must be deemed appropriate for extremity dosimeters and must be written in such a way as to promote worker safety. The information obtained from the processor visits and from the second performance test study has been combined with information obtained during the first study to provide recommendations for changes in the draft standard. The recommendations are divided into three areas: 1) the test procedures, 2) the irradiation categories and 3) the performance criterion.

TEST PROCEDURES

As a result of the information and experience obtained during the second performance testing study, two changes in the test procedures are recommended. The first recommendation is to include a statement requiring that the processor include instructions for properly mounting the dosimeters on the phantom. During the performance testing, some facilities did not indicate the appropriate way to mount the dosimeter on the phantom. In some cases the "best guess" of the testing laboratory turned out to be incorrect.

The second recommendation is to clarify the angular response (nonperpendicular incidence) test procedures. This recommendation is based on comments received from the processor facilities and the testing laboratory. Categories I, II, and VII should be excluded from the nonperpendicular incidence study on the basis of redundancy with other categories. Although it is important that the nonperpendicular incidence of the extremity dosimeters be known to the processor, a full test (as specified in Section D5 of Appendix D of ANSI N13.11) would be burdensome to the processor from the standpoint of expense and still would not provide as much information as desired because extremity dosimeters worn on fingers provide a wider range of angles with the source than do whole body dosimeters. Because of the mobility of the hands, the effect of nonperpendicular response could possibly be large; although, these effects have not been quantified. It is recommended that the draft standard specify that front and back irradiations be performed as a minimum, with angular responses at ±30° and ±60° recommended especially for wrist dosimeters.

IRRADIATION CATEGORIES

The data received during the performance testing and information received during the processor visits indicate that the following changes in the irradiation categories are appropriate:

- The upper value for the test range for non-accident categories should be reduced from 20 rem to 10 rem. This recommendation is made for three reasons: 1) extremely long exposure times are necessary to obtain a dose of 10 to 20 rem for some of the sources and are especially burdensome for the testing laboratory for the

amount of information obtained, 2) discussions with processors indicated that most extremity dosimeters are read on a monthly or per job basis; thus, an exposure of 10 to 20 rem on a single dosimeter could easily place the total quarterly dose above the regulatory limit, depending on the dose received on previous extremity dosimeters worn during that calendar quarter, and 3) the lower limit of the accident categories was already set at 10 rem.

- Single chip dosimeters are unable to discriminate between low-energy beta radiations, such as ^{204}Tl and higher-energy beta radiations, such as $^{90}Sr/^{90}Y$. For this reason, a similar concept to that employed by DOELAP (DOE 1986) and currently being considered by the ANSI N13.11 rewrite committee is recommended. This involves dividing Category VA into three parts (designated VA, VB and VC) where Categories VA (^{204}Tl source) and VB ($^{90}Sr/^{90}Y$ source) are for processors whose dosimeters cannot discriminate between energies, and Category VC (^{204}Tl and $^{90}Sr/^{90}Y$ sources) is for processors whose dosimeters are able to discriminate between energies.

- The results from both rounds of testing indicated a significant difference in the variances of the performance quotients obtained using different sources for Category IIIA (low-energy photons, general) although no variation was seen in the means. Therefore, we recommend that this category remain intact. However, following future testing of extremity dosimeters (such as would occur during subsequent performance tests or during a pilot test study), the result of irradiations with energies in the range of 20 to 40 keV (NIST filtered techniques M30 and S60) should be compared with the results of irradiations at 70 to 120 keV (NIST filtered techniques M150 and H150). If the performance index results obtained from the low-energy techniques are significantly different than those obtained from the higher-energy techniques, consideration should be given to subdividing this category.

- Neutron exposures to the extremities present a special problem. Current flux-to-dose equivalent conversion factors specified in regulations and recommendations of the NCRP are derived from the maximum value of dose equivalent in a 30-cm diameter cylindrical torso phantom. These values include secondary charged particles from neutron interactions as well as contributions from gamma rays from the absorption of neutrons by hydrogen atoms. Obviously, the cylindrical torso phantom model is not applicable for the extremities. Furthermore, because the extremities contain normal bone marrow, nonstochastic endpoints may be limiting before the risk of fatal cancer is comparable to whole body exposures. Thus, it would be inappropriate to include neutron exposures in an extremity standard until realistic flux-to-dose-equivalent conversion factors are derived for the extremities.

- The mixture categories should be divided into two categories: the first corresponding to photon mixtures and the second to mixtures of photons and beta particles. This method is similar to that used

in ANSI N13.11. Dividing the mixture category would allow the processors to participate in one type of mixture and not the other. During the performance study, several processors indicated that their service normally includes only photon mixtures and thus they did not want to participate with mixtures of photons and beta particles.

- The statement "the category in which each dosimeter was irradiated will be identified to the processor" should be included in the draft standard. The results discussed in this report indicate that although wrist dosimeters are able to discriminate between energies, single chip dosimeters are commonly unable to discriminate. Rather than treat the wrist and ring dosimeters differently, we recommend that the testing laboratory identify to the facilities the categories in which both ring and wrist dosimeters were irradiated. The draft standard should state that this decision will be re-evaluated at the time that the standard is rewritten. A future decision not to identify the categories during testing should be based on the amount of improvement in ring dosimeter design during the intervening time.

PERFORMANCE CRITERION

The performance criterion, including the magnitude of the tolerance level dictates the stringency of the performance testing. The higher the tolerance level, the larger the number of processors that will meet the performance criterion.

The current tolerance level given in the draft standard was derived to fulfill the goal that the annual assignment of dose equivalent should be within 30% of the conventionally true value for 95% of the personnel receiving in excess of one-tenth of the maximum permissible dose equivalent. However, the derivation of the criterion assumed a dosimeter exchange rate of four times per year and approximately uniform occupational exposures. Information obtained during the processor visits indicated that dosimeter exchanges occur primarily on a monthly basis, although some facilities exchange extremity dosimeters every 6 weeks or on a per-job basis. The dose rates vary with the job being performed, and in the case of nuclear power plants, the doses are rarely uniform during the year. Thus, the original basis for determining the tolerance level is not appropriate.

At the current tolerance level (0.35; with 0.40 for ^{204}Tl), the ring dosimeters met the tolerance level 70% of the time and the wrist dosimeters met the tolerance level 81% of the time. The improvement from the previous study was found to be between 15% and 18% over that observed during the initial performance test study, counting only those sources used in both studies. Although, it is possible that continued performance testing could produce an even greater passing rate, it should be noted that in some categories the results from Study 2 are worse than those from Study 1. The overall results, however, validate comments that were made during the facility visits that improvement would be expected with successive performance tests,

similar to the trend observed during the early tests for the NVLAP whole body dosimeters. This comment is also validated by the observation that the results are processor dependent. However, extremity dosimeters are generally less well developed and less frequently used than whole body dosimeters. Even though further performance testing may result in further increases in the passing rate, a more restrictive limit than that used for whole body dosimeters is not consistent with the less advanced stage of development in extremity dosimeters. A more restrictive limit would also not be necessary from the aspect of health effects to a worker because of the lower stochastic risk to the extremity as opposed to the whole body. The tolerance level could appropriately become more restrictive during future rewrites of the extremity standard if it was deemed appropriate based on future test results.

If the tolerance level for extremity dosimeters was changed to 0.5 for protection categories (III through VII) and 0.3 for the accident categories (to match those given in ANSI N13.11), using the data obtained during the current performance test study, a total of 81% of the ring dosimeters and 86% of the wrist dosimeters would have passed the performance criterion.

CONCLUSIONS AND RECOMMENDATIONS

Using the performance criterion and tolerance level given in the draft standard (HPSSC P/N 13.32, "Standard for the Performance Testing of Extremity Dosimeters", April, 1988), the passing rate for ring dosimeters was 70% and that for wrist dosimeters was 81%. This is an overall improvement of 15 to 18% from the results of the previous performance test (when comparing the results obtained using similar sources). The results of the current performance test indicated that the passing rates in individual categories ranged from 45% to 100%. The best performances (with a greater than 80% passing rate) were in the accident categories, and the low-energy photon protection category for both ring and wrist dosimeters and in the high-energy protection category for wrist dosimeters. The worst performances were observed in the beta-particle category (for ring dosimeters) and the neutron category (for wrist dosimeters), with passing rates of 45% and 68%, respectively. Variations were observed in the performance quotient results received from dosimeters irradiated by two different sources (or two different energy levels) within a single category. The most significant differences between sources (or energy levels) was observed for ring dosimeters irradiated in the low-energy photon category (NIST filtered techniques H150 and M150) and in the beta particle category (^{204}Tl and $^{90}Sr/^{90}Y$). For the wrist dosimeters, significant differences between sources (or energy levels) were observed in the low-energy category (NIST filtered techniques H150 and M150) and in the neutron category (moderated ^{252}Cf and unmoderated ^{252}Cf).

Based on the information obtained during the processor visits and the results obtained from the performance testing, it is recommended that the following changes be made to the draft standard:

- Category VA should be divided into three subcategories, designated VA, VB, and VC, where Categories VA (^{204}Tl source) and VB ($^{90}Sr/^{90}Y$ source) are for processors whose dosimeters cannot discriminate between energies, and Category VC (^{204}Tl and $^{90}Sr/^{90}Y$ sources) is for facilities whose dosimeters do discriminate between energies.

- Category IIIA (low-energy photons, general) should remain intact although results indicated a significant difference in the variances of the performance quotients obtained with different energy levels. However, the results of future performance test or pilot test studies should be reviewed to determine if the results obtained from irradiations with energies in the range of 20 to 40 keV (NIST filtered techniques M30 and S60) are significantly different from results obtained from irradiations with energies in the range of 70 to 120 keV (NIST filtered techniques M150 and H150). If the results are shown to be different, this category should be divided into two or more subcategories.

- The mixture category should be divided into two categories: the first corresponding to photon mixtures and the second to mixtures of photons and beta particles, thereby allowing the processors to participate in one type of mixture and not the other.

- The neutron category should be eliminated until appropriate flux-to-dose-equivalent conversion factors are derived.

- The testing laboratory should identify for processors the categories in which their dosimeters were irradiated. This recommendation is made in response to the inability of single-chip ring dosimeters to discriminate between energies.

- The tolerance level for the performance criterion should be changed to 0.30 for accident categories and 0.50 for protection categories to provide consistency with the performance criterion for dosimeters (ANSI 1983) and to avoid making the standard overly difficult for the processors of extremity dosimeters to pass. These tolerance levels would have resulted in a passing rate of 81% for ring dosimeters and 86% for wrist dosimeters.

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APPENDIX A

COMMENTS ON THE DRAFT STANDARD

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Personnel responsible for the extremity dosimetry programs at the processor facilities visited during this study were asked to comment on the draft standard. The following comments were made.

1. Categories

   Several processors questioned the inclusion of categories and sources that were not included in the NVLAP standard (ANSI N13.11), for example, Category VB (beta particles, slab uranium), Category VI (neutron), and the use of ^{204}Tl in Category VA. In addition, one of the processors questioned the use of the neutron category for shallow dose measurements since the specifications for neutron shallow dose are not defined. Processors using single chip dosimeters felt that they would always have difficulty passing Category VA using the ^{204}Tl source because of the difference in the calibration factors for $^{90}Sr/^{90}Y$ and ^{204}Tl and the inability to determine energies using a single chip dosimeter. Another processor indicated that without knowing the source the best they could do for the beta category was to pick a correction factor that lies midway between one for $^{90}Sr/^{90}Y$ and one for ^{204}Tl. Although they could hit the 0.40 performance criterion, they would have to have a very small standard deviation. They recommended an approach currently being discussed by the committee revising ANSI N13.11, that includes three subcategories, 1) $^{90}Sr/^{90}Y$, 2) ^{204}Tl, or 3) $^{90}Sr/^{90}Y$ and ^{204}Tl (without knowledge of the source).

2. Disclosing Radiation Type/Using Single Chip Dosimeters

   One processor suggested that for those processors using a single-chip dosimeter, an appropriate condition of accreditation might be a verification of the processor's knowledge of the energy of the radiation sources that their extremity dosimeters are exposed to. A second processor also held that accreditation should depend on a processor either proving that they had prior knowledge of the source of irradiation or passing the accreditation test without knowing the radiation source. The suggestion was also made that processors that used a single-chip dosimeter could use a wrist badge (multichip dosimeter) for a qualitative understanding of the spectra and the ring for a quantitative estimate of the dose.

3. Performance Criterion

   The comment was made several times that the performance criterion used in the draft standard for nonaccident dosimetry categories (0.35) was

substantially more conservative for extremity performance than ANSI N13.11 (ANSI 1983) is for whole body dosimeters (0.50).

4. Terminology

Several comments were received regarding the lack of careful or appropriate wording in the draft standard as well as areas needing additional clarification:

- There was some concern expressed over the use of the word "certification" rather than "accreditation," since the tests are run to determine accreditation, not certification.
- One commenter felt it was important to obtain angular response information while noting that it was not clear whether every category would be tested or if a processor could use their own sources.
- There was some confusion regarding the phantom design description, as well as the maximum useful interval for dosimetry irradiations.
- The explanation of the irradiation categories was confusing, specifically the explanation of the use of "only one type of radiation and one energy spectrum...per category in a given 3-to-6 month testing period."
- The reasoning behind the study of dosimeter performance at high doses was questioned because this study was not part of the test series and did not need to be performed by the test laboratory. It was unclear whether this study applied to all energies in each category. The commenter expressed concern in regard to the length of time necessary for high dose radiation to thallium and some of the low-energy photons.

5. Miscellaneous

The audit process was thought to be a good idea, especially the random processing of dosimeters with known exposure. It was felt that this might head off some of the "special attention" that processors may tend to give the test dosimeters.

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APPENDIX B

ASSESSMENT OF UNCERTAINTIES

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The dose equivalent, H, or dose, D, delivered to the sensitive element of a dosimeter can be expressed as follows:

Photon (sealed source):

$$D = \dot{X}(d_c) \cdot C_x \cdot \left(\frac{d_c}{d_p}\right)^2 \cdot \left(\frac{d_p}{d_p - d_e}\right)^2 \cdot f_Q \cdot t + D_B \qquad \text{(B.1)}$$

Photon (x-ray):

$$D = T(d_c) \cdot C_x \cdot M \cdot \left(\frac{d_c}{d_p}\right)^2 \left(\frac{d_p}{d_p - d_e}\right)^2 \cdot f_Q \cdot C_{TP} + D_B \qquad \text{(B.2)}$$

Beta:

$$D = \dot{D}(d_c) \cdot \left(\frac{d_c}{d_p}\right)^2 \cdot \left(\frac{d_p}{d_p - d_e}\right)^2 \cdot f_Q \cdot t \cdot C_t + D_B \qquad \text{(B.3)}$$

Neutron:

$$D = \left(\frac{3600}{4\pi}\right) \cdot N \cdot C_N \cdot t \cdot f_Q \left(\frac{1}{r^2 + r_p^2}\right) \left(\frac{r}{d_p}\right)^2 + D_d \qquad \text{(B.4)}$$

where $\dot{X}(d_C)$ is the exposure rate at the calibration distance, d_C, without phantom. This quantity is measured with NIST calibrated transfer chambers and verified with the NIST measurement quality assurance program. The uncertainty is systematic.

C_X is the conversion factor from Roentgens to rems in the presence of a phantom. The uncertainty for C_X is not included in the uncertainty.

d_C is the distance from the source to the calibration point. Its uncertainty is included in the uncertainty in $X(d_C)$, $T(d_C)$, or $D(d_C)$.

d_p is the distance from the source to the phantom surface. It is intended to be equal to d_c (or r). It is explicitly included so that random errors in determining d_p can be included in the uncertainty analysis.

d_e is the distance from the phantom surface to the midpoint of the sensitive element(s) when the dosimeter is mounted on the phantom for irradiation. Dosimeters are mounted parallel to the phantom surface. d_e can have both random and systematic uncertainties.

f_Q is the ratio of the dose rate at the position of the dosimeter to the dose rate at the center of the phantom. It has a systematic uncertainty.

t is the exposure time. The systematic uncertainty is minimized by timing measurements and, if necessary, appropriate correction factors. Random uncertainty is present.

D_B is the difference between the background dose or dose equivalent received by the test dosimeters and that received by the control dosimeters. This may occur during the time the test dosimeters are separated from the control dosimeters during an exposure period, normally less than 8 hours. The uncertainty is random.

$T(d_c)$ is the calibration value for the x-ray technique in units of exposure per charge recorded by the transmission chamber. This quantity is measured with a NIST-calibrated chamber and verified with the NIST measurement quality assurance program. The calibration factors are checked and adjusted quarterly unless problems are indicated by the internal quality control program. The uncertainty is systematic.

M is the reading of the transmission chamber. The uncertainty is random.

C_{TP} is the temperature and pressure correction factor required for the transmission chamber reading. The room conditions are monitored continuously. Most of the uncertainty is random. There may be some systematic uncertainty if the monitoring temperature device is not inside the transmission chamber.

$\dot{D}(d_c)$ is the dose rate measured with an in-house extrapolation chamber or measured by NIST. The in-house extrapolation chamber is calibrated using a source calibrated by NIST or traceable to NIST. The uncertainty is systematic because the calibration is determined before the test irradiations and changed infrequently (e.g., quarterly).

C_t is the transmission factor necessary if the NIST calibration was performed at a different tissue depth than the source calibration. The uncertainty is systematic. This factor is typically unity with no uncertainty.

N is the neutron emission rate, calibrated by NIST. The uncertainty is due to the NIST calibration and source decay. Source decay uncertainty is small. The total uncertainty is systematic.

C_N is the dose-equivalent conversion factor recommended by NIST. This factor is used by the testing laboratory and the participants, so that no irradiation uncertainty is associated with its use.

r is the theoretical distance to the calibration point. The ratio r/d_p represents the assumed unity value associated with the measurement of the source to phantom distance.

r_p is the distance from the center of the phantom to the dosimeter position. Random uncertainties result from the placement of the dosimeter. Systematic uncertainties occur because of the placement of the position of the sensitive element in the dosimeter.

TABLE B.1. Irradiation Uncertainties

Variable	Type(a)	Percent Uncertainty: Bremsstrahlung X-ray (1 m & 2 m)	K X-ray (50 cm)	Neutron (50 cm)	^{137}Cs	^{90}Sr
$T(d_C)$	Sys	1.7(b)	2.3(b)	-	-	-
	Ran	0.5	0.5		-	-
d_p	Ran	0.1	0.4	0.4	0.1	0.6
d_e	Ran	0.1	0.4	-	0.1	0.6
	Sys	0.3	1.2	-	0.3	1.3
f_Q	Sys	1.5	2.0	1.0	0.5	1.0
t	Ran	-	-	0.5	<0.5	<0.5
M	Ran	0.5	0.5	-	-	-
C_{TP}	Ran	0.2	0.2	-	-	-
D_B	Ran	0.3	0.3	0.3	<0.3	<0.3
N	Sys	-	-	1.5	-	-
r_p	Sys	-	-	0.3	-	-
$S(d_C)$	Sys	-	-	-	1.6	-
$D(d_C)$	Sys	-	-	-	-	2.0
Total Sys		2.3	3.3	1.8	1.7	2.6
Total Ran		0.8	1.0	0.7	0.6	1.0
Total Sys + Ran		3.1	4.3	3.5	2.3	3.6

(a) Sys = systematic uncertainty
Ran = random uncertainty

(b) 0.5% systematic and 0.5% random reproducibility uncertainty included to allow for the movement of the tube head between Bremsstrahlung and k-fluorescence techniques.

APPENDIX C

COMPILATION OF DOSIMETER PERFORMANCE DATA

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COMPILATION OF DOSIMETER PERFORMANCE DATA

This appendix contains the performance data for the dosimeters tested in this study. The results for the ring dosimeters are presented in Tables C.1 through C.8. The results for the wrist dosimeters are presented in Tables C.9 through C.17. The tables are organized by category. Each table contains the processor identification codes (A-K) and the dosimeter type codes (A-V) for the dosimeters submitted for that specific category. The tables list the bias, standard deviation, and the sum of the absolute value of the bias and the standard deviation for each round of testing.

The initial results are based on the processors knowing the identity of those dosimeters irradiated in Categories I, II, and VI, but not in Categories III, IV, V, and VII. These results are labeled "Initial Results." The tables for Categories III, IV, V, and VII include the revised results received from the processors following disclosure of the dosimeters irradiated in each of the categories. These results are labeled "Categories Identified." In addition, all tables include the corrected Round 2 results that were based on the list of doses delivered to the Round 1 dosimeters. These results are labeled "Corrected Round 2 Results."

TABLE C.1. Category I - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Corrected Round 2 Results[a]		
				Bias (B)	Standard Deviation (S)	IBI + S	Bias (B)	Standard Deviation (S)	IBI + S
B	V	1	M150	-0.082	0.099	0.182			
		2	M150	-0.495	0.145	0.639	-0.495	0.145	0.639
B	T	1	M150	VOID[b]	VOID[b]	VOID[b]			
		2	M150	-0.106	0.122	0.229	-0.106	0.122	0.229
B	U	1	M150	-0.222	0.084	0.306			
		2	M150	-0.263	0.087	0.350	-0.263	0.087	0.350
D	E	1	M150	0.176	0.082	0.258			
		2	M150	0.094	0.040	0.133	0.094	0.040	0.133
H	K	1	M150	0.135	0.088	0.223			
		2	M150	0.180	0.059	0.239	0.180	0.059	0.239

(a) Based on disclosure of Round 1 results.
(b) Data submitted could not be correlated to test results.

TABLE C.2. Category II - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Corrected Round 2 Results[a]		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S
A	A	1	^{137}Cs	-0.172	0.026	0.198			
		2	^{137}Cs	1.836	4.471	6.307	2.182	4.940	7.122
B	V	1	^{137}Cs	0.033	0.086	0.119			
		2	^{137}Cs	-0.394	0.205	0.598	-0.394	0.205	0.598
B	T	1	^{137}Cs	VOID[b]	VOID	VOID			
		2	^{137}Cs	-0.121	0.072	0.193	-0.121	0.072	0.193
B	U	1	^{137}Cs	-0.132	0.110	0.242			
		2	^{137}Cs	-0.165	0.048	0.213	-0.165	0.048	0.213
D	E	1	^{137}Cs	-0.031	0.027	0.058			
		2	^{137}Cs	-0.007	0.056	0.063	-0.007	0.056	0.063
H	K	1	^{137}Cs	-0.083	0.049	0.133			
		2	^{137}Cs	-0.011	0.075	0.085	-0.011	0.075	0.085
J	Q	1	^{137}Cs	-0.105	0.121	0.227			
		2	^{137}Cs	0.366	0.126	0.492	0.366	0.126	0.492
K	R	1	^{137}Cs	0.041	0.092	0.134			
		2	^{137}Cs	-0.201	0.110	0.311	NR[c]	NR	NR

(a) Based on disclosure of Round 1 results.
(b) Data submitted could not be correlated to test results.
(c) No results were received from processor.

TABLE C.3. Category IIIA - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
B	V	1	H150	0.005	0.085	0.090	0.005	0.085	0.090			
		2	M150	-0.428	0.126	0.554	-0.428	0.126	0.554	-0.428	0.126	0.554
B	V	1	H150	VOID(b)	VOID	VOID	VOID	VOID	VOID			
		2	M150	-0.083	0.111	0.193	-0.083	0.111	0.193	-0.083	0.111	0.193
B	V	1	H150	-0.165	0.054	0.219	-0.165	0.054	0.219			
		2	M150	-0.309	0.171	0.480	-0.309	0.171	0.480	-0.309	0.171	0.254
C	B	1	H150	-0.147	0.024	0.170	-0.147	0.024	0.170			
		2	M150	0.665	0.070	0.735	0.665	0.070	0.735	0.665	0.070	0.735
D	E	1	H150	-0.001	0.031	0.031	0.038	0.034	0.071			
		2	M150	0.073	0.069	0.142	0.073	0.069	0.142	0.073	0.069	0.142
E	H	1	H150	0.204	0.119	0.323	NR(c)	NR	NR			
		2	M150	-0.116	0.098	0.213	NR	NR	NR	NR	NR	NR
H	K	1	H150	0.069	0.051	0.120	0.069	0.051	0.120			
		2	M150	0.195	0.046	0.241	0.195	0.046	0.241	0.195	0.046	0.241

(a) Based on disclosure of Round 1 results.
(b) Data submitted could not be correlated to test results.
(c) No results were received from processor.

TABLE C.4. Category IIIB - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
D	E	1	55-85 keV	0.151	0.050	0.201	0.082	0.047	0.129			
		2	15-20 keV	0.157	0.095	0.252	-0.043	0.083	0.126	-0.043	0.083	0.126
H	K	1	55-85 keV	0.209	0.086	0.295	0.572	0.112	0.684			
		2	15-20 keV	0.232	0.103	0.335	0.601	0.133	0.735	0.601	0.133	0.735

(a) Based on disclosure of Round 1 results.

TABLE C.5. Category IV - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
A	A	1	^{60}Co	-0.168	0.043	0.210	-0.168	0.043	0.210			
		2	^{137}Cs	1.524	3.899	5.424	1.524	3.899	5.424	1.954	4.562	6.516
B	V	1	^{60}Co	0.260	0.141	0.401	0.260	0.141	0.401			
		2	^{137}Cs	-0.321	0.159	0.480	-0.321	0.159	0.480	-0.321	0.159	0.480
B	T	1	^{60}Co	VOID(b)	VOID	VOID	VOID	VOID	VOID			
		2	^{137}Cs	0.008	0.222	0.230	0.008	0.222	0.230	0.008	0.222	0.230
B	U	1	^{60}Co	-0.147	0.098	0.245	-0.147	0.098	0.245			
		2	^{137}Cs	-0.124	0.065	0.189	-0.124	0.065	0.189	-0.124	0.065	0.189
C	B	1	^{60}Co	-0.329	0.036	0.366	-0.329	0.036	0.366			
		2	^{137}Cs	-0.042	0.012	0.054	-0.042	0.012	0.054	-0.042	0.012	0.054
D	E	1	^{60}Co	-0.071	0.035	0.107	0.083	0.053	0.136			
		2	^{137}Cs	-0.168	0.049	0.216	-0.079	0.063	0.143	-0.079	0.063	0.143
E	H	1	^{60}Co	0.003	0.013	0.016	NR(c)	NR	NR			
		2	^{137}Cs	-0.276	0.048	0.324	NR	NR	NR	NR	NR	NR
G	J	1	^{60}Co	0.227	0.155	0.382	0.227	0.155	0.382			
		2	^{137}Cs	0.162	0.082	0.245	0.162	0.082	0.245	0.162	0.082	0.245
H	K	1	^{60}Co	-0.128	0.044	0.172	-0.128	0.044	0.172			
		2	^{137}Cs	-0.082	0.056	0.138	-0.082	0.056	0.138	-0.082	0.056	0.138
J	Q	1	^{60}Co	-0.196	0.154	0.350	-0.196	0.154	0.350			
		2	^{137}Cs	0.391	0.110	0.501	0.391	0.110	0.501	0.391	0.110	0.501
K	R	1	^{60}Co	0.102	0.076	0.178	0.102	0.076	0.178			
		2	^{137}Cs	0.127	0.180	0.307	0.127	0.180	0.307	NR	NR	NR

(a) Based on disclosure of Round 1 results.
(b) Data submitted could not be correlated to test results.
(c) No results were received from processor.

TABLE C.6. Category VA - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results[a]		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
B	V	1	^{204}Tl	-0.270	0.117	0.388	-0.270	0.117	0.388			
		2	^{90}Sr	-0.324	0.216	0.540	-0.324	0.216	0.540	-0.324	0.216	0.540
B	T	1	^{204}Tl	VOID[b]	VOID	VOID	VOID	VOID	VOID			
		2	^{90}Sr	0.151	0.112	0.263	0.151	0.112	0.263	0.151	0.112	0.263
B	U	1	^{204}Tl	-0.342	0.084	0.426	-0.342	0.084	0.426			
		2	^{90}Sr	-0.012	0.061	0.073	-0.012	0.061	0.073	-0.012	0.061	0.730
C	B	1	^{204}Tl	-0.934	0.011	0.945	0.053	0.180	0.233			
		2	^{90}Sr	-0.111	0.032	0.143	3.444	0.160	3.603	3.444	0.160	3.603
E	H	1	^{204}Tl	-0.834	0.026	0.860	NR[c]	NR	NR			
		2	^{90}Sr	-0.394	0.034	0.428	NR	NR	NR	NR	NR	NR
H	K	1	^{204}Tl	-0.747	0.028	0.776	-0.671	0.038	0.709			
		2	^{90}Sr	-0.158	0.051	0.207	0.097	0.067	0.164	0.097	0.067	0.164
J	Q	1	^{204}Tl	-0.135	0.042	0.178	-0.135	0.042	0.178			
		2	^{90}Sr	0.403	0.145	0.549	0.403	0.145	0.549	0.403	0.145	0.549

(a) Based on disclosure of Round 1 results.
(b) Data submitted could not be correlated to test results.
(c) No results were received from processor.

TABLE C.7. Category VB - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
B	V	1	U-slab	-0.074	0.094	0.168	-0.074	0.094	0.168			
		2	U-slab	-0.446	0.134	0.580	-0.446	0.134	0.580	-0.446	0.134	0.580
B	T	1	U-slab	VOID(b)	VOID	VOID	VOID	VOID	VOID			
		2	U-slab	-0.073	0.097	0.169	-0.073	0.097	0.169	-0.073	0.097	0.169
B	U	1	U-slab	-0.245	0.070	0.315	-0.245	0.070	0.315			
		2	U-slab	-0.343	0.370	0.713	-0.343	0.370	0.713	-0.343	0.370	0.713
D	E	1	U-slab	-0.456	0.052	0.508	-0.087	0.083	0.170			
		2	U-slab	-0.486	0.013	0.499	-0.144	0.023	0.166	-0.144	0.023	0.166
H	K	1	U-slab	-0.344	0.089	0.433	0.312	0.178	0.490			
		2	U-slab	-0.355	0.036	0.391	0.290	0.071	0.361	0.290	0.071	0.361
J	Q	1	U-slab	-0.045	0.089	0.134	-0.045	0.089	0.134			
		2	U-slab	0.185	0.152	0.337	0.185	0.152	0.337	0.185	0.152	0.337

(a) Based on disclosure of Round 1 results.
(b) Data submitted could not be correlated to test results.

TABLE C.8. Category VII - Ring Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results: Bias (B)	Initial Results: Standard Deviation (S)	Initial Results: |B| + S	Categories Identified: Bias (B)	Categories Identified: Standard Deviation (S)	Categories Identified: |B| + S	Corrected Round 2 Results[a]: Bias (B)	Corrected Round 2 Results[a]: (S)	Corrected Round 2 Results[a]: |B| + S
B	T	1	$^{60}Co/^{90}Sr$	VOID[b]	VOID	VOID	VOID	VOID	VOID			
		2	M150/^{90}Sr	-0.082	0.191	0.253	-0.062	0.191	0.253	-0.062	0.191	0.253
B	U	1	$^{60}Co/^{90}Sr$	0.012	0.136	0.148	0.012	0.136	0.148			
		2	M150/^{90}Sr	-0.121	0.038	0.159	-0.121	0.038	0.159	-0.121	0.038	0.159
B	V	1	$^{60}Co/^{90}Sr$	0.233	0.086	0.319	0.233	0.086	0.319			
		2	M150/^{90}Sr	-0.291	0.116	0.407	-0.291	0.116	0.407	-0.291	0.116	0.407
C	B	1	$^{60}Co/^{90}Sr$	-0.313	0.064	0.377	-0.313	0.064	0.377			
		2	M150/^{90}Sr	-0.078	0.030	0.108	-0.078	0.030	0.108	-0.078	0.030	0.108
H	K	1	$^{60}Co/^{90}Sr$	-0.153	0.121	0.274	-0.153	0.121	0.274			
		2	M150/^{90}Sr	-0.067	0.078	0.145	-0.067	0.078	0.145	-0.067	0.078	0.145
J	Q	1	$^{60}Co/^{90}Sr$	0.059	0.129	0.189	0.059	0.129	0.189			
		2	M150/^{90}Sr	0.317	0.137	0.454	0.317	0.137	0.454	0.317	0.137	0.454

(a) Based on disclosure of Round 1 results.
(b) Data submitted could not be corrected to test results.

TABLE C.9. Category I - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results Bias (B)	Initial Results Standard Deviation (S)	Initial Results |B| + S	Corrected Round 2 Results[a] Bias (B)	Corrected Round 2 Results[a] Standard Deviation (S)	Corrected Round 2 Results[a] |B| + S
D	F	1	M150	0.075	0.055	0.130			
		2	M150	-0.010	0.031	0.041	-0.010	0.031	0.041
F	I	1	M150	0.254	0.225	0.480			
		2	M150	-0.007	0.170	0.177	-0.007	0.170	0.177
H	M	1	M150	0.069	0.070	0.139			
		2	M150	0.121	0.040	0.162	0.083	0.049	0.132
H	N	1	M150	0.198	0.068	0.266			
		2	M150	0.168	0.064	0.232	-0.019	0.053	0.072
I	O	1	M150	0.027	0.075	0.102			
		2	M150	0.060	0.062	0.123	0.060	0.062	0.123
K	S	1	M150	0.205	0.089	0.294			
		2	M150	1.434	2.850	4.284	NR[b]	NR	NR

(a) Based on disclosure of Round 1 results.
(b) No results were received from processor.

TABLE C.10. Category II - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results Bias (B)	Initial Results Standard Deviation (S)	Initial Results |B| + S	Corrected Round 2 Results(a) Bias (B)	Corrected Round 2 Results(a) Standard Deviation (S)	Corrected Round 2 Results(a) |B| + S
D	F	1	^{137}Cs	-0.045	0.017	0.061			
		2	^{137}Cs	0.011	0.041	0.052	0.011	0.041	0.052
F	I	1	^{137}Cs	-0.107	0.046	0.152			
		2	$^{1}{}^{137}Cs$	-0.100	0.075	0.175	-0.100	0.075	0.175
H	M	1	^{137}Cs	-0.082	0.081	0.162			
		2	^{137}Cs	-0.030	0.068	0.098	-0.070	0.056	0.126
H	N	1	^{137}Cs	-0.016	0.045	0.061			
		2	^{137}Cs	-0.074	0.059	0.133	-0.074	0.059	0.133
I	O	1	^{137}Cs	-0.124	0.060	0.184			
		2	^{137}Cs	-0.087	0.065	0.152	-0.087	0.065	0.152
K	S	1	^{137}Cs	0.164	0.190	0.354			
		2	^{137}Cs	0.093	0.036	0.129	NR(b)	NR	NR

(a) Based on disclosure of Round 1 results.
(b) No results were received from processor.

TABLE C.11. Category IIIA - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
C	C	1	H150	0.058	0.049	0.107	0.058	0.049	0.107			
		2	M150	0.199	0.286	0.485	0.199	0.286	0.485	0.199	0.286	0.485
D	F	1	H150	-0.779	0.007	0.786	0.234	0.290	0.524			
		2	M150	-0.079	0.120	0.199	-0.079	0.120	0.199	-0.079	0.120	0.199
F	I	1	H150	0.060	0.233	0.292	-0.150	0.098	0.248			
		2	M150	-0.343	0.112	0.455	-0.343	0.112	0.455	-0.343	0.112	0.455
H	M	1	H150	0.057	0.047	0.104	-0.019	0.018	0.037			
		2	M150	-0.101	0.203	0.304	-0.124	0.183	0.307	-0.124	0.183	0.307
H	N	1	H150	0.180	0.119	0.299	0.193	0.086	0.280			
		2	M150	0.102	0.086	0.187	0.187	0.066	0.253	-0.003	0.055	0.058
I	O	1	H150	-0.028	0.052	0.078	-0.026	0.052	0.078			
		2	M150	-0.125	0.056	0.181	-0.125	0.056	0.181	-0.125	0.056	0.181
K	S	1	H150	0.130	0.156	0.286	0.130	0.156	0.286			
		2	M150	-0.105	0.125	0.230	-0.105	0.125	0.230	NR(b)	NR	NR

(a) Based on disclosure of Round 1 results.
(b) No results were received from processor.

TABLE C.12. Category IIIB - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results Bias (B)	Initial Results Standard Deviation (S)	Initial Results |B| + S	Categories Identified Bias (B)	Categories Identified Standard Deviation (S)	Categories Identified |B| + S	Corrected Round 2 Results(a) Bias (B)	Corrected Round 2 Results(a) (S)	Corrected Round 2 Results(a) |B| + S
D	F	1	55-65 keV	0.185	0.026	0.211	0.391	0.160	0.551			
		2	15-20 keV	0.082	0.113	0.194	0.082	0.113	0.194	0.082	0.113	0.194
F	I	1	55-65 keV	0.070	0.273	0.343	-0.026	0.296	0.323			
		2	15-20 keV	0.124	0.065	0.189	0.124	0.065	0.189	0.124	0.065	0.189
H	M	1	55-65 keV	-0.042	0.055	0.097	-0.034	0.040	0.074			
		2	15-20 keV	0.273	0.049	0.322	0.273	0.049	0.322	0.441	0.055	0.496
H	N	1	55-65 keV	0.118	0.108	0.226	0.177	0.071	0.248			
		2	15-20 keV	0.051	0.495	0.546	-0.119	0.392	0.511	-0.119	0.392	0.511

(a) Based on disclosure of Round 1 results.

TABLE C.13. Category IV - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
C	C	1	^{60}Co	0.007	0.029	0.036	0.007	0.029	0.036			
		2	^{137}Cs	0.002	0.057	0.059	0.002	0.057	0.059	0.002	0.057	0.059
D	F	1	^{60}Co	0.103	0.037	0.140	0.103	0.037	0.140			
		2	^{137}Cs	-0.009	0.028	0.037	-0.009	0.028	0.037	-0.009	0.028	0.037
F	I	1	^{60}Co	-0.151	0.071	0.222	-0.151	0.071	0.222			
		2	^{137}Cs	-0.015	0.099	0.114	-0.015	0.099	0.114	-0.015	0.099	0.114
H	M	1	^{60}Co	-0.069	0.073	0.142	-0.104	0.056	0.160			
		2	^{137}Cs	-0.049	0.056	0.105	-0.068	0.052	0.120	-0.068	0.052	0.120
H	N	1	^{60}Co	-0.024	0.062	0.086	-0.062	0.035	0.098			
		2	^{137}Cs	-0.050	0.123	0.173	-0.092	0.081	0.173	-0.092	0.081	0.173
I	O	1	^{60}Co	-0.052	0.027	0.079	-0.052	0.027	0.079			
		2	^{137}Cs	-0.011	0.078	0.089	-0.011	0.078	0.089	-0.011	0.078	0.089
K	S	1	^{60}Co	0.007	0.085	0.092	0.007	0.085	0.092			
		2	^{137}Cs	0.021	0.042	0.064	0.021	0.042	0.064	NR(b)	NR	NR

(a) Based on disclosure of Round 1 results.
(b) No results were received from processor.

TABLE C.14. Category VA - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
C	C	1	^{204}Tl	-0.044	0.070	0.114	-0.044	0.070	0.114			
		2	^{90}Sr	0.255	0.079	0.334	0.255	0.079	0.334	0.255	0.079	0.334
D	F	1	^{204}Tl	-0.044	0.168	0.213	-0.044	0.168	0.213			
		2	^{90}Sr	-0.187	0.033	0.221	-0.187	0.033	0.221	-0.187	0.033	0.221
F	I	1	^{204}Tl	3.700	1.063	4.763	3.700	1.063	4.763			
		2	^{90}Sr	-0.009	0.065	0.074	-0.009	0.065	0.074	-0.009	0.065	0.074
H	M	1	^{204}Tl	-0.723	0.061	0.784	-0.723	0.061	0.784			
		2	^{90}Sr	-0.127	0.042	0.169	-0.127	0.042	0.169	-0.127	0.042	0.169
H	N	1	^{204}Tl	-0.033	0.227	0.260	-0.033	0.227	0.260			
		2	^{90}Sr	-0.141	0.098	0.239	-0.048	0.069	0.116	-0.048	0.069	0.116
I	O	1	^{204}Tl	0.486	0.445	0.931	0.486	0.445	0.931			
		2	^{90}Sr	0.002	0.081	0.083	0.002	0.081	0.083	0.002	0.081	0.083
K	S	1	^{204}Tl	-0.754	0.038	0.792	-0.754	0.038	0.792			
		2	^{90}Sr	0.026	0.064	0.091	0.026	0.064	0.091	NR(b)	NR	NR

(a) Based on disclosure of Round 1 results.
(b) No results were received from processor.

TABLE C.15. Category VB - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
D	F	1	U-slab	-0.195	0.105	0.299	-0.195	0.105	0.299			
		2	U-slab	-0.161	0.035	0.196	-0.161	0.035	0.196	-0.161	0.035	0.196
F	I	1	U-slab	-0.058	0.292	0.349	-0.058	0.292	0.349			
		2	U-slab	0.048	0.082	0.130	0.048	0.082	0.130	0.048	0.082	0.130
H	M	1	U-slab	-0.401	0.112	0.513	-0.003	0.190	0.193			
		2	U-slab	-0.399	0.043	0.442	1.929	4.475	6.403	1.929	4.475	6.403
H	N	1	U-slab	-0.048	0.030	0.077	-0.048	0.030	0.077			
		2	U-slab	-0.054	0.119	0.172	-0.054	0.119	0.172	-0.054	0.119	0.172

(a) Based on disclosure of Round 1 results.

TABLE C.16. Category VI - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results Bias (B)	Initial Results Standard Deviation (S)	Initial Results |B| + S	Corrected Round 2 Results(a) Bias (B)	Corrected Round 2 Results(a) Standard Deviation (S)	Corrected Round 2 Results(a) |B| + S
C	D	1	Bare ^{252}Cf	-0.065	0.245	0.310			
		2	Mod. ^{252}Cf	0.205	0.041	0.245	0.205	0.041	0.245
D	G	1	Bare ^{252}Cf	-0.048	0.096	0.144			
		2	Mod. ^{252}Cf	-0.103	0.184	0.287	-0.103	0.184	0.287
F	I	1	Bare ^{252}Cf	-0.108	0.199	0.307			
		2	Mod. ^{252}Cf	0.135	0.445	0.580	0.135	0.445	0.580
H	L	1	Bare ^{252}Cf	-0.923	0.010	0.932			
		2	Mod. ^{252}Cf	0.327	1.149	1.476	0.379	1.204	1.583
H	M	1	Bare ^{252}Cf	-0.900	0.006	0.906			
		2	Mod. ^{252}Cf	-0.043	0.071	0.114	-0.043	0.071	0.114
H	N	1	Bare ^{252}Cf	0.144	0.116	0.259			
		2	Mod. ^{252}Cf	-0.156	0.146	0.302	-0.156	0.146	0.302
I	P	1	Bare ^{252}Cf	-0.037	0.204	0.241			
		2	Mod. ^{252}Cf	0.071	0.060	0.131	0.071	0.060	0.131
K	Q	1	Bare ^{252}Cf	-0.062	0.189	0.251			
		2	Mod. ^{252}Cf	0.650	0.275	0.925	NR(b)	NR	NR

(a) Based on disclosure of Round 1 results.
(b) No results were received from processor.

TABLE C.17. Category VII - Wrist Dosimeters

Processor Code	Dosimeter Type Code	Round	Source	Initial Results			Categories Identified			Corrected Round 2 Results(a)		
				Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	Standard Deviation (S)	|B| + S	Bias (B)	(S)	|B| + S
C	C	1	$^{60}Co/^{90}Sr$	0.300	0.081	0.381	0.015	0.057	0.073			
		2	M150/^{90}Sr	0.258	0.078	0.336	0.008	0.063	0.071	0.008	0.063	0.071
D	G	1	$^{60}Co/^{90}Sr$	-0.142	0.019	0.161	-0.142	0.019	0.161			
		2	M150/^{90}Sr	0.230	0.080	0.310	0.230	0.080	0.310	0.230	0.080	0.310
F	I	1	$^{60}Co/^{90}Sr$	-0.017	0.036	0.053	-0.017	0.036	0.053			
		2	M150/^{90}Sr	-0.646	0.039	0.685	-0.646	0.039	0.685	-0.646	0.039	0.685
H	M	1	$^{60}Co/^{90}Sr$	-0.109	0.080	0.189	-0.109	0.080	0.189			
		2	M150/^{90}Sr	-0.137	0.057	0.194	-0.137	0.057	0.194	-0.137	0.057	0.194
H	N	1	$^{60}Co/^{90}Sr$	-0.048	0.035	0.083	-0.048	0.035	0.083			
		2	M150/^{90}Sr	-0.096	0.075	0.171	-0.096	0.075	0.171	-0.096	0.075	0.171
I	O	1	$^{60}Co/^{90}Sr$	-0.040	0.039	0.080	-0.040	0.039	0.080			
		2	M150/^{90}Sr	-0.044	0.094	0.138	-0.044	0.094	0.138	-0.044	0.094	0.138
K	S	1	$^{60}Co/^{90}Sr$	-0.392	0.032	0.424	-0.392	0.032	0.424			
		2	M150/^{90}Sr	-0.475	0.027	0.502	-0.475	0.027	0.502	NR(b)	NR	NR

(a) Based on disclosure of Round 1 results.
(b) No results were received from processor.