NBS TECHNICAL NOTE 978

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

Nationwide Survey of Cobalt-60 Teletherapy Dosimetry

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+Technical Note

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Between September 1974 and December 1977 the National Bureau of Standards, in cooperation with the Bureau of Radiological Health, performed a study of the accuracy with which a prescribed absorbed dose of cobalt-60 gamma radiation is delivered to a specified point in a water phantom. Approximately two-thirds of the cobalt-60 teletherapy units in the U.S. were surveyed by mail, using a rugged thermoluminescence dosimetry system. The dose given by participants was evaluated from dosimeter response, and information supplied by participants was used to check their computations of the dose delivered. In this nationwide study, 83 percent of the units surveyed yielded dose interpretations within 5 percent of the requested dose, 13 percent yielded differences between 5 and 10 percent, and 4 percent of the dose interpretations differed by more than 10 percent from the dose requested. Sources of discrepancies are discussed, and the results of this survey are compared with those of other dosimetry surveys.

Key words: Absorbed dose; cobalt-60 gamma radiation; computation check; dose interpretation; mailings; survey; teletherapy; thermoluminescence dosimeters; water phantom.

1. INTRODUCTION

Cobalt-60 gamma ray teletherapy sources are widely used for cancer therapy, both in this country and around the world. The accuracy with which a prescribed absorbed dose is delivered to a tumor has been shown to be crucial to treatment success.[1] In order to assess the ability of cobalt-60 teletherapy users in the United States to deliver a prescribed dose of radiation to a water phantom, the National Bureau of Standards (NBS) has carried out a measurement assurance program using mailed thermoluminescence dosimeters. Other programs of this type have been successful in assessing the performance of cobalt-60 teletherapy users elsewhere (see sec. 6). The survey described in this paper includes over two-thirds of the approximately 1000 teletherapy facilities currently in use in this country.

2. ADMINISTRATIVE PROCEDURE

2.1 Contacting the Prospective Participants

Lists of teletherapy licensees were supplied to NBS by the Bureau of Radiological Health (BRH) at a rate of one list of about 50 licensees every six weeks. Each licensee was sent a form letter (table 1) which explained the purpose of the survey and asked for voluntary participation. Table 2 is a copy of the questionnaire which was included for the recipient to indicate whether or not he was willing to participate. This form was to be returned to NBS in a stamped self-addressed envelope which was enclosed. If there was no response from the licensee after four weeks, a follow-up form letter was sent (table 3), including the same questionnaire and return envelope. This approach was quite useful in obtaining additional participants. Almost half of the licensees who were sent follow-up letters agreed to participate.

Over the three years of the survey, there were 1020 licensees' names and addresses supplied by BRH. All but 144 licensees returned the questionnaire. Of those returning the questionnaire, 656 indicated willingness to participate*, while 74 refused participation. The remaining 146 indicated that they did not have a cobalt-60 teletherapy unit at the time of inquiry.

2.2. The Initial Survey

The initial survey comprised 24 mailing cycles, each approximately six weeks long and consisting of the following phases:

a. Mailing Phase

Each mailing involved between 35 and 50 sets of six dosimeters. Approximately ten days before the dosimeters were to be mailed, licensees who had expressed willingness to participate were sent an announcement (table 4) that the dosimeters were to be mailed soon. Then, at the beginning of the six-week mailing cycle, one set of dosimeters was mailed to the participants for each cobalt-60 teletherapy beam to be surveyed. Included with each set was a copy of the announcement sent the previous week, instructions for irradiation of the dosimeters, and an information form for the participant to complete.

The instruction form is shown in table 5. The participants were asked to compute the time necessary to deliver 3.0 grays (300 rad) at a depth of 1 centimeter in a large water phantom for a 10 cm x 10 cm field size and their normal treatment distance. They were then to irradiate 5 of the 6 dosimeters in air, on top of the cardboard shipping carton, for this time at this distance. The sixth dosimeter was to be left blank as a control. The essentials of the prescribed irradiation geometry are shown in figure 1. Participants were asked that the irradiations be performed under conditions duplicating as closely as possible the routine patient irradiations, and that the individuals carrying out the irradiations be those routinely involved in patient set-up and treatment.

The three-page information form (table 6) was in two parts. In the first part (page 1) the participant was asked to supply time and date of irradiation, distance, field size, irradiation time, and identification of the person doing the exposures and the person supplying the information. This page could be readily completed by a technician and was to be returned with the dosimeters. The second part (pages 2 and 3) was to be filled out by the physicist in charge. It required information about beam calibration and parameters used by the participant to determine the absorbed-dose rate used for the dosimeter irradiations. This latter information was used by NBS to check the participant's absorbed-dose computation.

b. Evaluation and Reporting Phase

After the dosimeters had been returned to NBS by the participants, dose interpretations from dosimeter responses were made, according to the procedure described in section 4.1.

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*Some of these licensees had more than one cobalt-60 teletherapy unit to be surveyed.

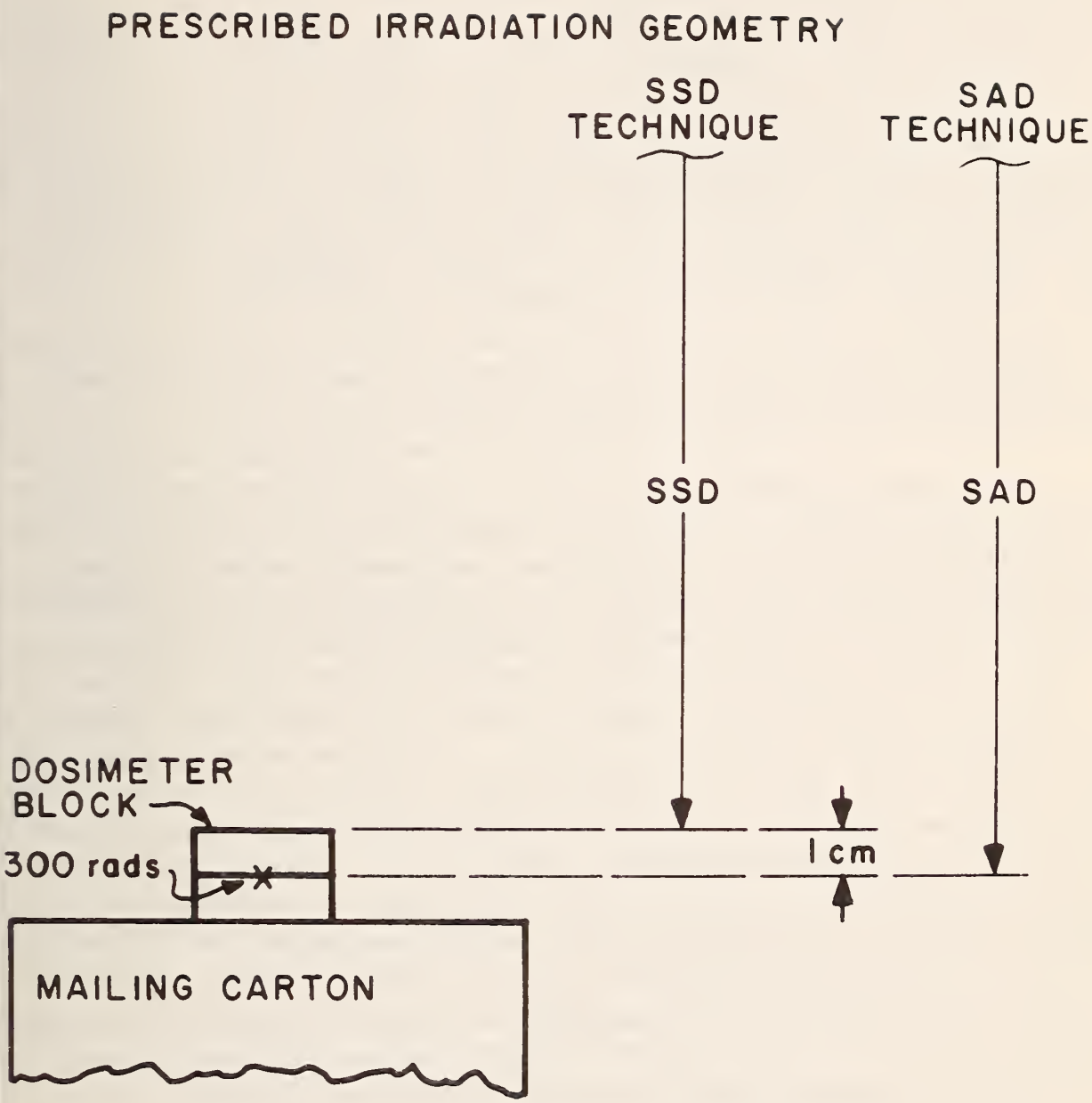

Figure 1. Prescribed Irradiation Geometry. The participant was to employ his usual distance and technique (either source-to-surface, SSD, or source-to-axis, SAD).

This generally occurred during the fifth and the sixth week of the mailing cycle. Upon completion of this evaluation, each participant was sent the absorbed-dose interpretation obtained from the response of each dosimeter involved in the particular mailing, with his own dosimeters identified. Also included were: the value of absorbed dose as computed by NBS from the calibration information (if supplied by the participant), tables of factors and methods used in this computation, and some general information about the survey. The text of the report is given in table 7. Table 8 shows the various methods used to compute absorbed-dose rate at a 1-centimeter depth in a water phantom. The factors employed in the computation are listed in table 9. Copies of the reports were given to the Bureau of Radiological Health but without participant identification. (Performance of all participants is known only to NBS and is treated as confidential information.)

2.3 The Follow-up Survey

As a part of the last mailing cycles of the initial survey and in one additional mailing cycle, follow-up studies were performed. They were:

a. Statistical Verification of Survey Results

A sub-sample of the original participants was selected for further work. The chosen sub-sample consisted of 10 percent of the participants whose results were within 5 percent of the requested dose, one-half of the participants whose results differed from the requested dose by between 5 and 10 percent, and all participants whose results differed by more than 10 percent. A total of 143 participants were involved in this re-study.

b. Check on Influence of Incomplete Participation

It was furthermore desired to assess the influence upon the statistical survey results of the fact that certain licensees had declined to participate or had not responded to the initial invitation to participate. For this purpose, a randomly selected sample of 10 percent of this group was contacted and 13 of them were persuaded to participate at the end of the survey. It was impossible to determine exactly how many of the licensees who did not respond to the initial inquiries were no longer using a cobalt-60 therapy unit. However, during the selection of participants from the non-respondents, it was found that one-third, or 7 of the 21 licensees selected, were no longer doing cobalt-60 therapy. If this ratio is applied to the entire group of non-respondents, then the 13 licensees who were persuaded to participate in the last round represent eight percent of the licensees who had not responded or declined to participate in the original survey.

3. DESCRIPTION OF DOSIMETRY SYSTEM

3.1 Choice of Detector

A mailable dosimetry system should be suitable for storing irradiation information and should be mechanically rugged and thermally stable. For these reasons, thermoluminescence (TL) detectors are generally chosen for mailed systems. They do exhibit a certain amount of fading of the stored information, but the fading characteristics are well known. Also, since ours was to be a long-term project covering a large number of facilities with relatively few dosimeters, it was necessary for the chosen detector to withstand repeated use.

Thus, the TL material chosen had to have a relatively small dependence of TL response on thermal and irradiation history. For this reason, CaF_2:Mn was selected. The commercially available dosimeters consisted of two pieces of pressed crystalline CaF_2:Mn in contact with a metallic heater strip, enclosed in a quartz bulb with a neutral atmosphere. During shipment and irradiation, these bulbs were encased in black polystyrene blocks, as shown in figure 2. One bulb each was placed into one of the halves of a block, each half having dimensions 7.6 cm x 5.0 cm x 1.0 cm. The halves were then screwed together with Nylon screws. The plastic was of sufficient thickness for maximum electron buildup in polystyrene at the bulb surface in a cobalt-60 gamma ray beam. Black plastic was chosen since CaF_2:Mn is sensitive to prolonged exposure to visible light. The orientation of the bulb with respect to the incident beam was fixed by bending one of the bulb pins. This also fixed the orientation during readout, which was found to be necessary for good reproducibility. The orientation chosen was such that neither of the TL pieces in the bulb was shielded from the gamma ray beam by the heater strip, and that luminescence emission was not blocked by the heater strip during readout.

Initially 280 bulbs were used for the survey. They were divided into two batches. The first batch, purchased earlier, consisted of 88 dosimeters numbered from 3 through 91. The second batch of 192 was numbered from 101 through 292. The two batches differed from each other mainly in their average response, the former batch being more sensitive than the latter batch. In order to increase the number of teletherapy units surveyed per mailing cycle an additional set of 100 bulbs was purchased during the course of the survey. This third batch was assigned numbers from 301 through 400. Its sensitivity was about midway between the two earlier batches.

3.2 Readout Technique

The dosimeters were read out in a commercial assembly which included a bulb-heating unit using resistive heating of the heater strip, and a cooled photomultiplier for converting light output to electric current. A current integrator was used to determine the total TL signal, which was transferred automatically to paper tape upon completion of readout. For flexibility in the selection of readout parameters, the entire assembly was controlled by an electronic timer in a circuit designed at NBS to permit independent variation of total heating and current-integration times.

Since the TL dosimetry system employed relied on annealing of the CaF_2:Mn material solely during readout, a readout technique was chosen that enabled one to read dosimeters irradiated over the entire contemplated dose range without appreciable interference from incandescence or from release of residual trapped electrons. Yet, to prolong the life of the dosimeters, heating power was kept at a minimum. An annealing time of 21 seconds was used throughout. For readout of dosimeters mailed to the participants and of all associated calibration dosimeters which received exposures of 100 roentgens or more, the heater current was 6.0 amperes, which produced close to the highest permitted thermal load to the dosimeter. For the three further readouts required during each cycle, a heater current of 5.5 amperes was sufficient. For details on calibration and readout see section 4.1.

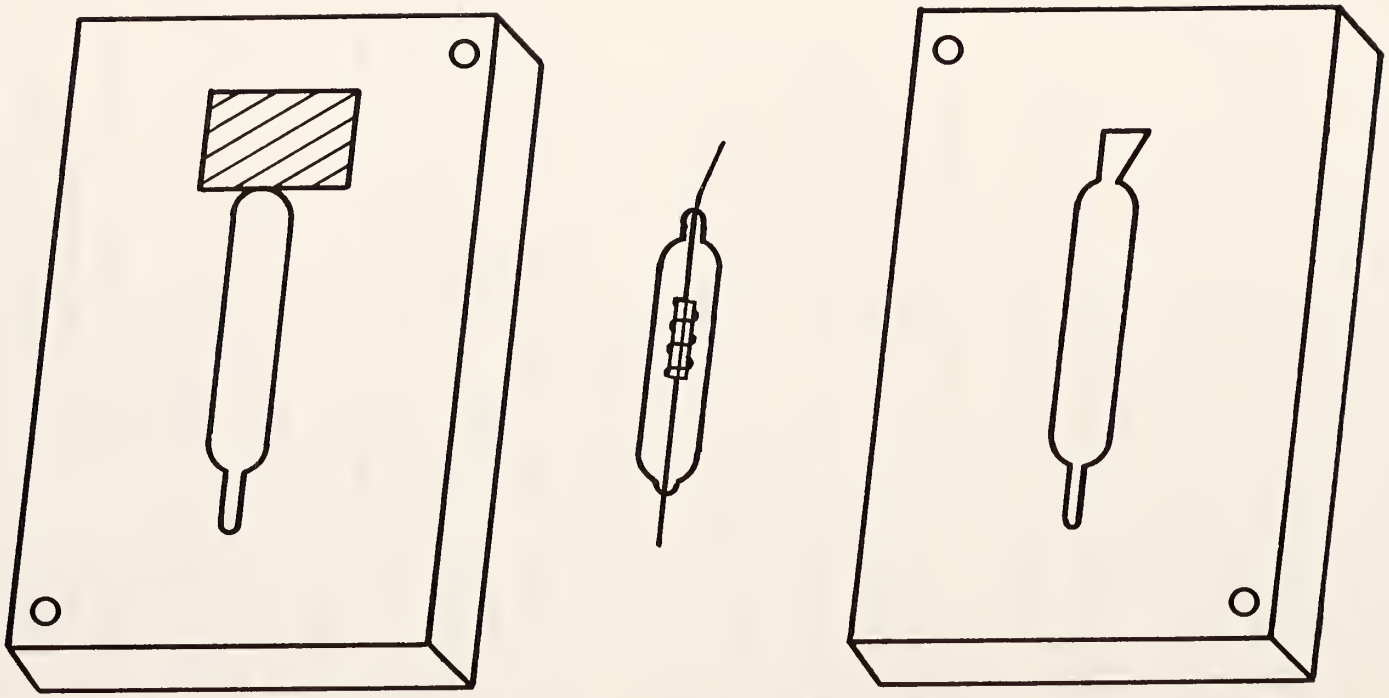

Figure 2. Schematic Diagram of Bulb Dosimeter and Polystyrene Holder.

Initially, signal-integration times of 14 and 16 seconds for the 6- and 5.5-ampere readouts, respectively, were used since they were found to produce maximum discrimination against incandescence, while including most of the glow peaks. However, these integration times were not sufficient for the readout of the most recently acquired batch of TL dosimeters, whose main glow peaks lay at slightly higher temperatures than those of the older batches. Thus, the integration times for all the dosimeters were changed to 16 and 19.5 seconds for the 6- and 5.5-ampere readouts, respectively. With these longer integration times, it was still possible to discriminate successfully against incandescence. Figure 3 shows typical glow curves, with the beginning and the end of the current-integration periods noted.

4. DOSE INTERPRETATION FROM TL RESPONSE

4.1 Method

Prior to their initial use in the program, all dosimeters were administered a series of ten identical cobalt-60 gamma ray exposures between 3 and 5 roentgens and were read out by the method described below. The results of these successive readings yielded initial values of individual response per unit exposure (sensitivity) and indications of the extent of reproducibility of dosimeter response. The relative standard deviation of repeated individual dosimeter readings was found to range from about 0.1 to 2 percent, with an average of 0.8 percent.

During each mailing cycle, each dosimeter was read four times. The first readout yielded the raw dosimeter response to the irradiation administered by the participant (or by NBS if that dosimeter had been kept at NBS for use in the calibration procedure). The three subsequent readouts were for correction purposes. Five days after the first readout, each dosimeter was read a second time, for a determination of its residual response level. Then on the next two days, each dosimeter was exposed to the same low level (3 to 5 R) and read out approximately 4 hours later, for a determination of its individual sensitivity. The data from each of the four readouts were fed into a Univac 1108 computer, and were analyzed by a program developed for the purpose. This program used an algorithm involving the determination of absorbed dose received by a dosimeter from dosimeter response, corrected for (a) relative sensitivity of the dosimeters to cobalt-60 gamma radiation, (b) change in photomultiplier sensitivity during readout, and (c) fading. The following is a discussion of these three corrections:

(a) The sensitivity of each dosimeter was checked between successive mailings. This was necessary since sensitivity was found to change with repeated use, as is illustrated in figure 4. A correction for the difference in response of individual dosimeters was determined by exposing each dosimeter to the same low level (3 to 5 R) of cobalt-60 gamma radiation, with the time intervals between irradiation and readout adjusted to eliminate the need for fading corrections. The average of the responses after two such exposures, performed on successive days, formed the basis of the sensitivity correction for each dosimeter.* A further correction was required for each dosimeter because of the presence of

* It might have been preferable to use as the basis for the sensitivity correction the mean of the two response values before and after a given irradiation-and-readout cycle. This would have tended to average out the fluctuations in the sensitivity changes recorded between successive irradiation and readout cycles (see fig. 4).

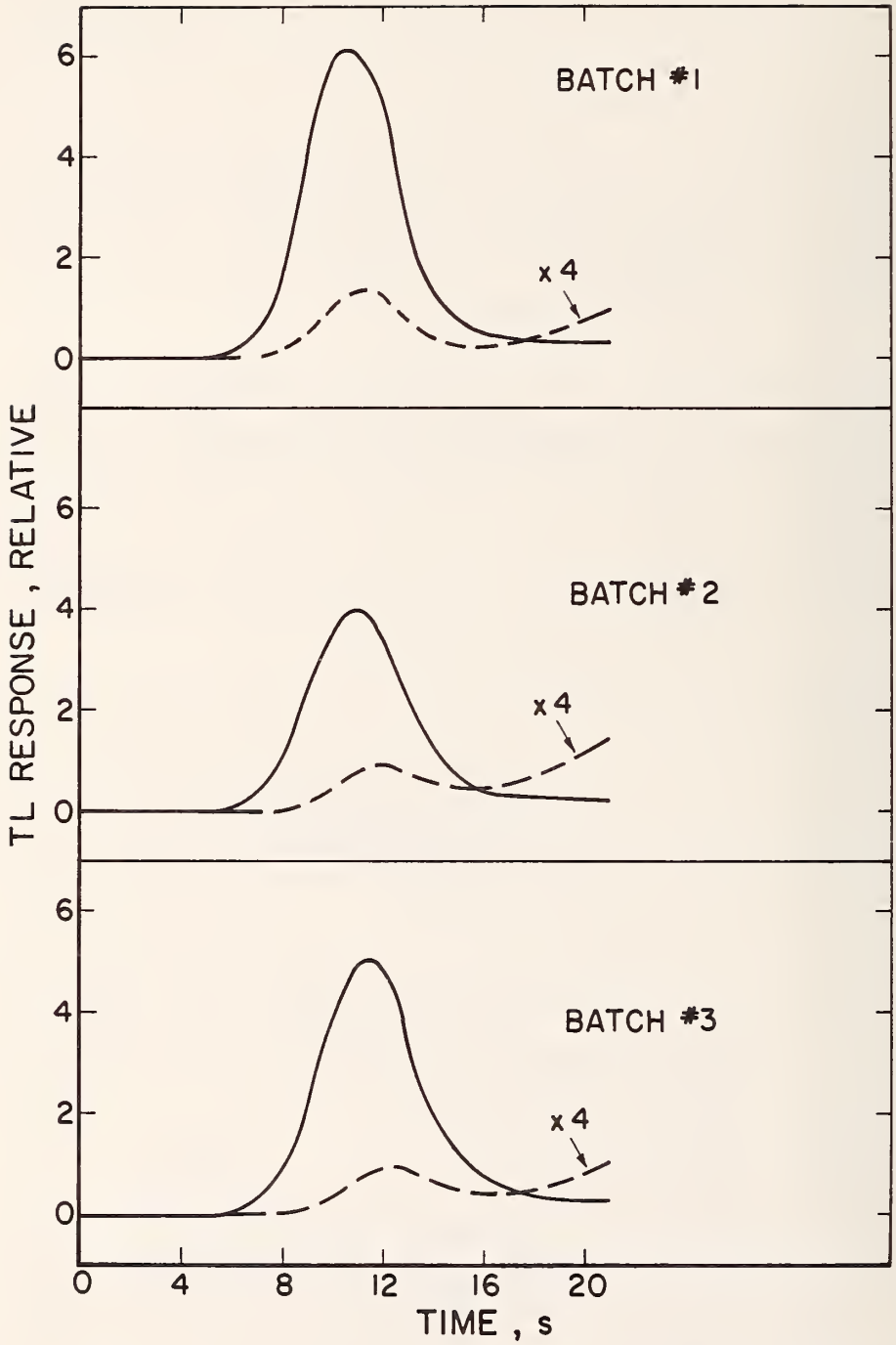

Figure 3. Typical Glow Curves for the Three Dosimeter Batches. The continuous lines represent the response to a 3–5 R exposure, while the dashed line (drawn with the ordinate multiplied by four) represents the sum of the residual glow curve from a previous 300–R exposure, and incandescence. The current–integration period started at time zero and extended to 19.5 seconds.

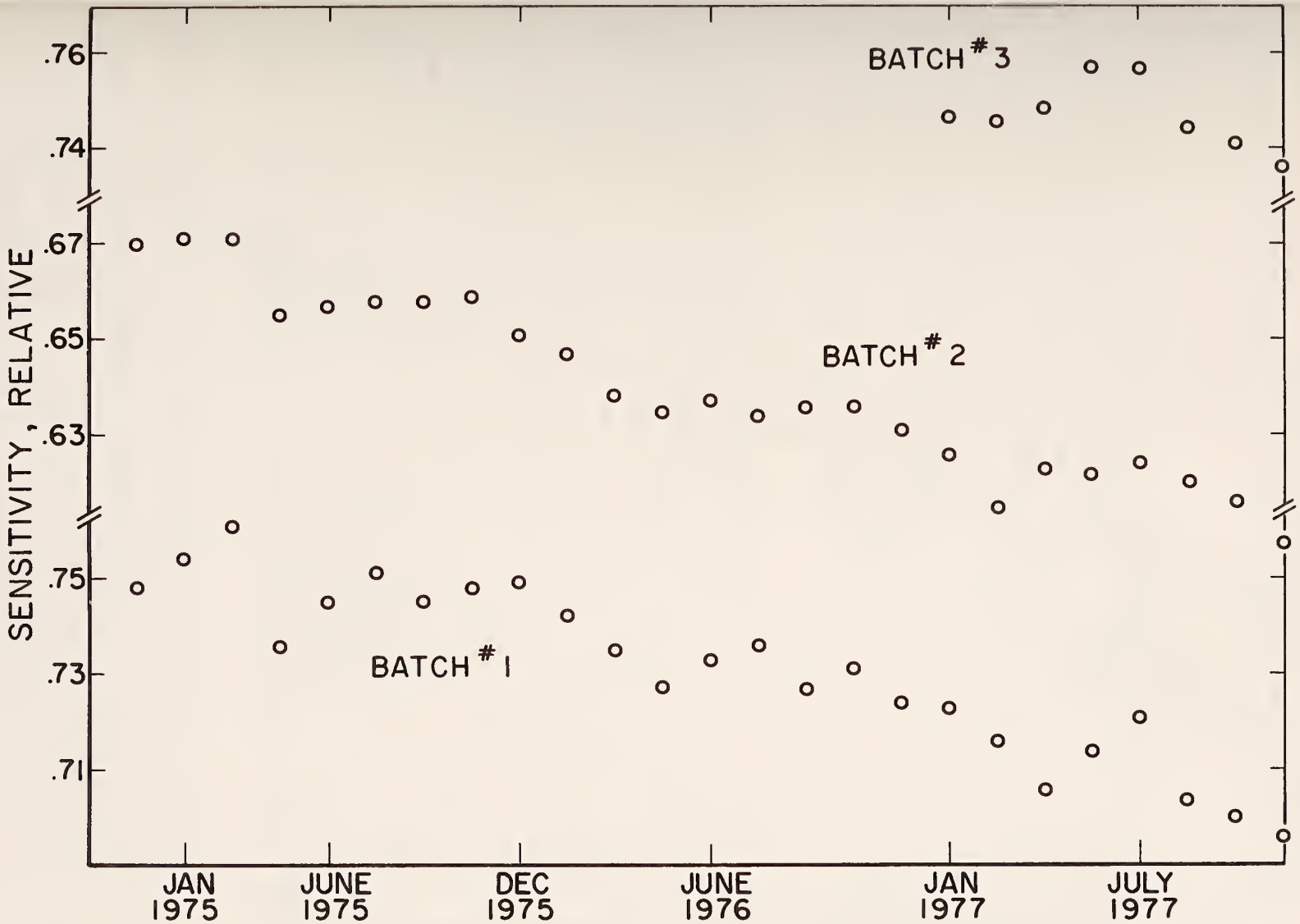

Figure 4. Change in Dosimeter Sensitivity (Response per Unit Exposure) with Repeated Use. The points shown for each batch were obtained with one dosimeter representative of the batch. No attempt was made to identify the origin of the occasional pronounced sensitivity drops, such as those shown between January and June, 1975.

residual thermoluminescence, the magnitude of which depended upon the absorbed dose received during the mailing cycle. This residual TL was measured in a second readout of each dosimeter five days after the first readout. For the irradiation and readout sequence employed, this correction amounted to between 0.5 and 1.5 percent of the response to a 3 to 5 roentgen exposure.

(b) A correction for change of photomultiplier sensitivity during readout was necessary. To convert the TL signal to an electric current for integration, a bialkali-dynode type photomultiplier was used at 620 volts. This voltage led to current signals of about 10 microamperes for the TL response to 300 rads. Under these operating conditions, the photomultiplier gain was found to increase monotonically by almost 4 percent during the roughly 3 hours required for the readout of about 270 dosimeters, of which about 200 received $\sim$ 300 rads. A suitable correction for this increase was obtained with the aid of readings taken at regular intervals during the readout sequence of the constant light source built into the reader. This gain change was probably due to insufficient cooling of the photomultiplier at high signal levels, since an overhaul of the cooling fan motor decreased the effect considerably. After this overhaul was performed, the gain change during readout was never larger than 2 percent.

(c) During the three years of the survey, fading characteristics of the dosimeters were monitored at regular intervals. Initially the reduction of the TL signal with an increase in the delay between irradiation and readout ("fading") was found to be about 4 percent over the decade between 20 and 200 hours, while it was only about 2.5 percent over the subsequent 500 hours. In the course of the survey, it was noticed that the first dosimeter batch (lowest numbers) was fading to a lesser extent than the other batches, and that it was therefore necessary to apply two different fading corrections, one for the first batch and one for the other two batches, which were found to exhibit the same degree of fading. An example of the fading behavior is shown in figure 5, where TL response relative to that obtained in a readout 24 hours after irradiation is plotted against time in hours between irradiation and readout. From the figure it is seen that the correction for fading applied to the readings of the dosimeters exposed by the participants varied between 3 and 7 percent for the usually encountered 170-to-700-hour delay between irradiation and readout. The time and date of irradiation supplied by the participants on page 1 of the information form (table 6) gave us the data necessary for the application of the appropriate fading correction.

The corrected dosimeter response was obtained by applying each of the above corrections to the raw response data. Implicit in this procedure is the assumption that relative dosimeter sensitivity is independent of irradiation level. Absorbed dose was derived from the corrected response with the aid of an absolute dosimeter calibration carried out by administering known cobalt-60 gamma ray exposures to a group of dosimeters in a geometry identical to that used by the participants. Several dozen dosimeters were employed, with the absorbed dose delivered being computed from exposure using method 3 (table 8) and parameters from table 9. These calibration dosimeters were read out along with the

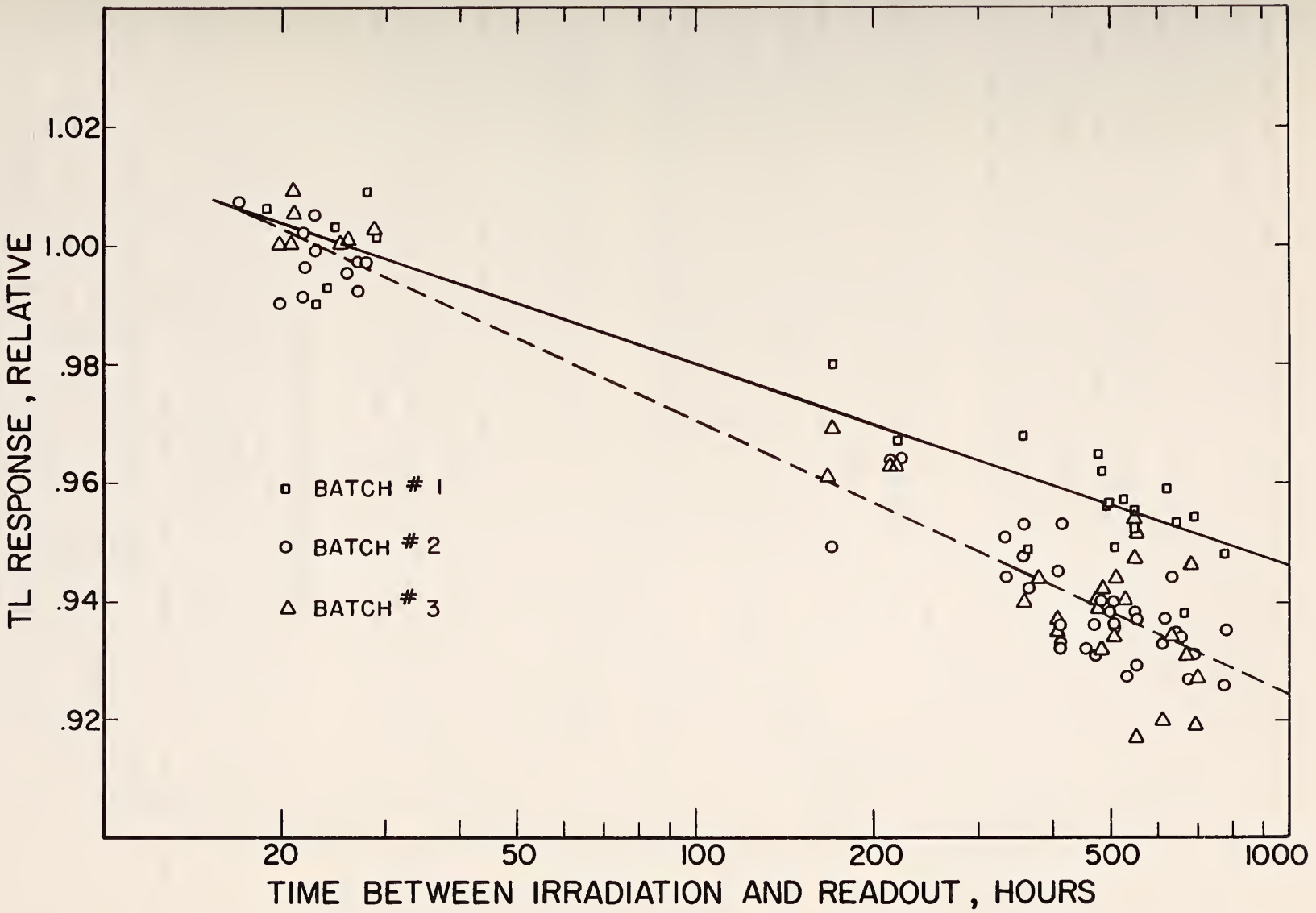

Figure 5. Dosimeter Fading, by Batch. Continuous line: Least-squares fit of the response data from batch #1, normalized to the average response obtained for readouts eighteen to thirty hours after irradiation. Dashed line: Least-squares fit of the response data from batches #2 and #3, normalized to the average response obtained for readouts eighteen to thirty hours after irradiation.

dosimeter returned by the participants, and were handled identically in subsequent readouts and irradiations.

4.2 Uncertainties in NBS Method of Determining Absorbed Dose from Dosimeter Response

A valid assessment by NBS of the participants' ability to deliver a prescribed absorbed dose necessitated a knowledge of the uncertainty in the NBS procedure for determining absorbed dose from dosimeter response. In table 10, values are given for the systematic and random uncertainties inherent in the NBS procedure for determining absorbed dose. The systematic uncertainties, stemming from the use of dosimeter-calibration and fading curves, were obtained from the least-squares fits of these curves. The individual systematic uncertainties were taken to be three times the average standard deviations of the predicted values in the ranges of interest. The total systematic uncertainty then was derived as the sum of the individual uncertainties listed.

The total random uncertainty was determined by considering both the limits in the reproducibility of the response of any one dosimeter (obtained prior to the start of the survey, see sec. 4.1), and the variation in the response from dosimeter to dosimeter. The limit in the reproducibility of the response was taken to be three times the relative standard deviation, S, of the readings of a dosimeter after repeated irradiations and readouts (2.4 %). This same reproducibility limit also is reflected in the correction factor applied to the reading of an individual dosimeter, to take into account the variation in response from dosimeter to dosimeter. The total random uncertainty in the determination of absorbed dose from dosimeter response then was computed as the square root of the sum of the squares of these two uncertainties (3.4 %).

The corresponding random uncertainty of the average of the absorbed-dose values obtained from the readings of five dosimeters then was obtained by division by $\sqrt{5}$, finally leading to an estimate of about 4 percent (or ± 12 rad at the 300-rad level) for the algebraic sum of the uncertainty due to the total systematic and random errors. This is taken to be the total uncertainty of the NBS dose interpretation from the average response of five dosimeters. The hard-to-assess uncertainties associated with the generally accepted values of the parameters and constants used in the computation of absorbed dose from exposure were not included.

5. DISCUSSION OF SURVEY RESULTS

5.1. Dose Interpretation from Response of Irradiated Dosimeters

Figure 6 shows the distribution of the differences between the absorbed dose of 300 rads to be delivered by the participants and the NBS dose interpretations from the average of the responses of the five dosimeters they irradiated. The total number of dosimeter sets involved was 906, of which 751 or 83 percent yielded dose interpretations with ± 5 percent of the requested dose of 300 rads in water. In view of the error analysis presented in the previous section, differences of 5 percent or more (in either direction) in the average dose interpretation must be considered significant. Seventeen percent or 155 sets yielded dose interpretations differing by more than 5 percent from the requested dose, with 34 of these (4%) differing by more than 10 percent. This distribution can be replaced by a Gaussian

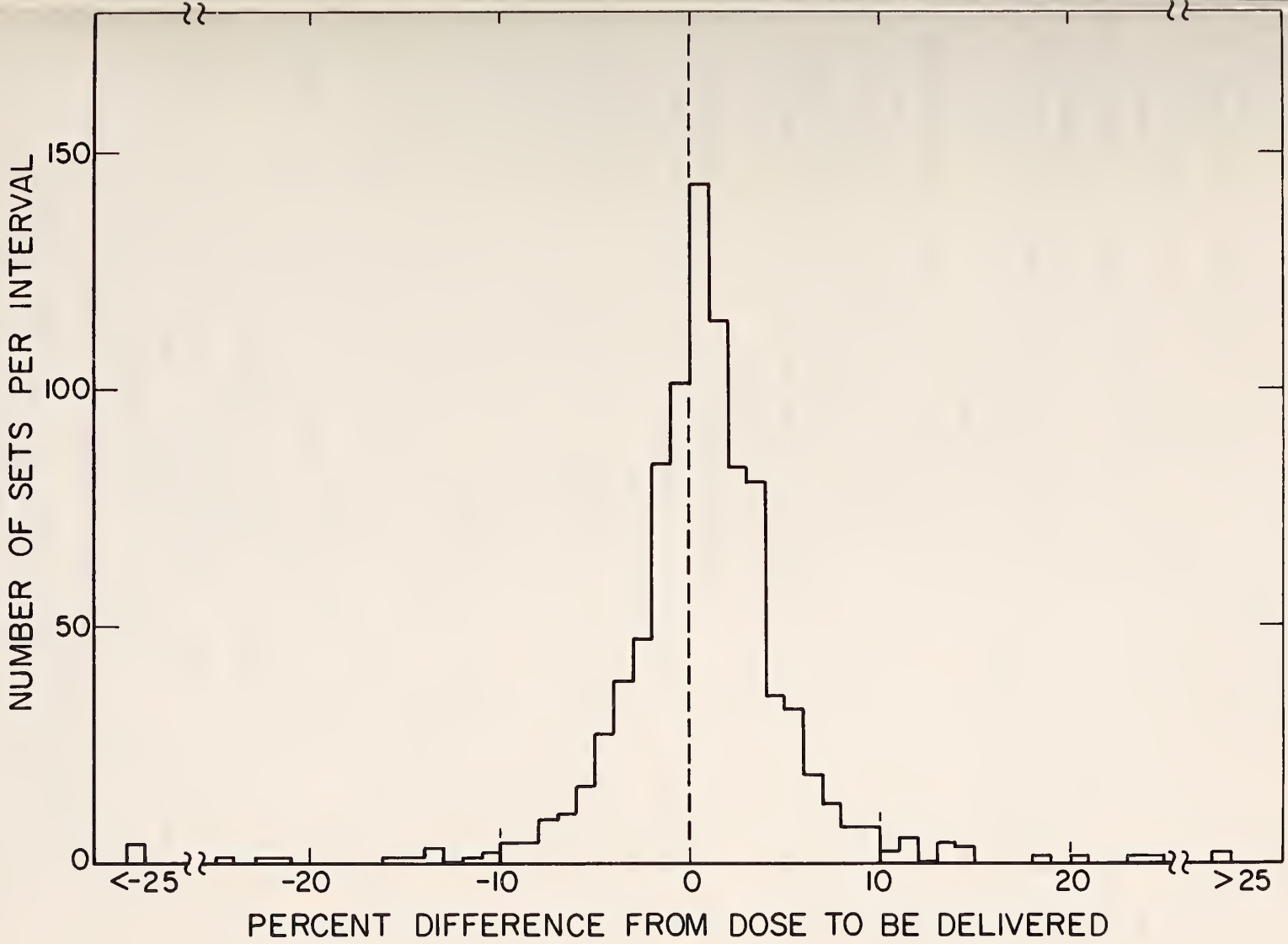

Figure 6. Performance of Participants Involved in the Survey. Shown is the difference, in percent, between the dose to be delivered by the participants and the NBS dose interpretation from the average of the responses of the five irradiated dosimeters. Total numbers of participants: 812; total number of sets: 906.

envelope with a width, σ, of 3.8 percent. There is a positive bias in the data, the average deviation for all sets shown being +0.7 percent. We believe that the reason for this bias is that most participants used the conversion factor from exposure to absorbed dose in soft tissue (.957) rather than that to absorbed dose in water (.965) which was used at NBS in the dosimeter calibrations. (For the purposes of this study, we did not make a distinction between absorbed dose in soft tissue and water, see table 5). The results for the participants who were selected for a re-survey are shown in figure 7. There was a definite improvement in the group for which the dose delivered initially differed from 300 rads by more than 10 percent. The survey results of the 143 selected participants show essentially the same performance breakdown as the group as a whole, i.e., 83 percent within 5 percent, 12 percent between 5 and 10 percent, and 5 percent with deviations outside of 10 percent. This is interesting because this group contained most of the participants who had performed poorly, but only 10 percent of those who had performed well.

A histogram of the results for the sample of initial non-participants who participated at the end of the survey is shown in figure 8. Although the statistics are poor, they indicate the same performance breakdown as for the other groups surveyed. Hence there is reason to believe that the fact that some licensees did not respond to the initial communications or refused to participate did not detract from the generality of our results.

5.2 Sources of Error in Delivered Dose

Only through laboratory visits is it possible to isolate all sources of error in performance. The NBS study did not involve any laboratory visits. However, from the information forms returned with the dosimeters, it was often possible to separate errors in calculation of the absorbed-dose rate from errors in dose delivery. Distinct from both of these were discrepancies which arose because participants misread or misunderstood the instructions. Thus, in the course of the survey, we received dosimeters which had been irradiated to 30, 200, 900 or 100 rads. The latter value occurred more than once, undoubtedly because of confusion caused by the concurrent Nuclear Regulatory Commission TLD survey. This type of misunderstanding of the instructions accounts for the discrepancies greater than 25 percent shown in figure 6. We were able to ascertain that further errors resulted when participants failed to place the dosimeters on the shipping carton for irradiation. This generally resulted in larger dose interpretations than expected because of an increase in the back-scatter contribution to the dosimeter response. Also, irradiating dosimeter blocks upside-down sometimes led to small deviations ($< 4\%$).

A relatively large number of errors concerned delivery of the prescribed dose. The most common one involved improper setting of the mechanical timer by one minute in either the positive or negative direction. This error was identified 15 times in the course of the approximately 4500 doses that were delivered, indicating that the timer systems in general use may be in need of improvement.

We later learned that other delivery errors had resulted from irradiation at improper distances, transposition of digits in treatment times, attenuators not accounted for, dosimeters irradiated twice by mistake, and errors caused by timer and other equipment

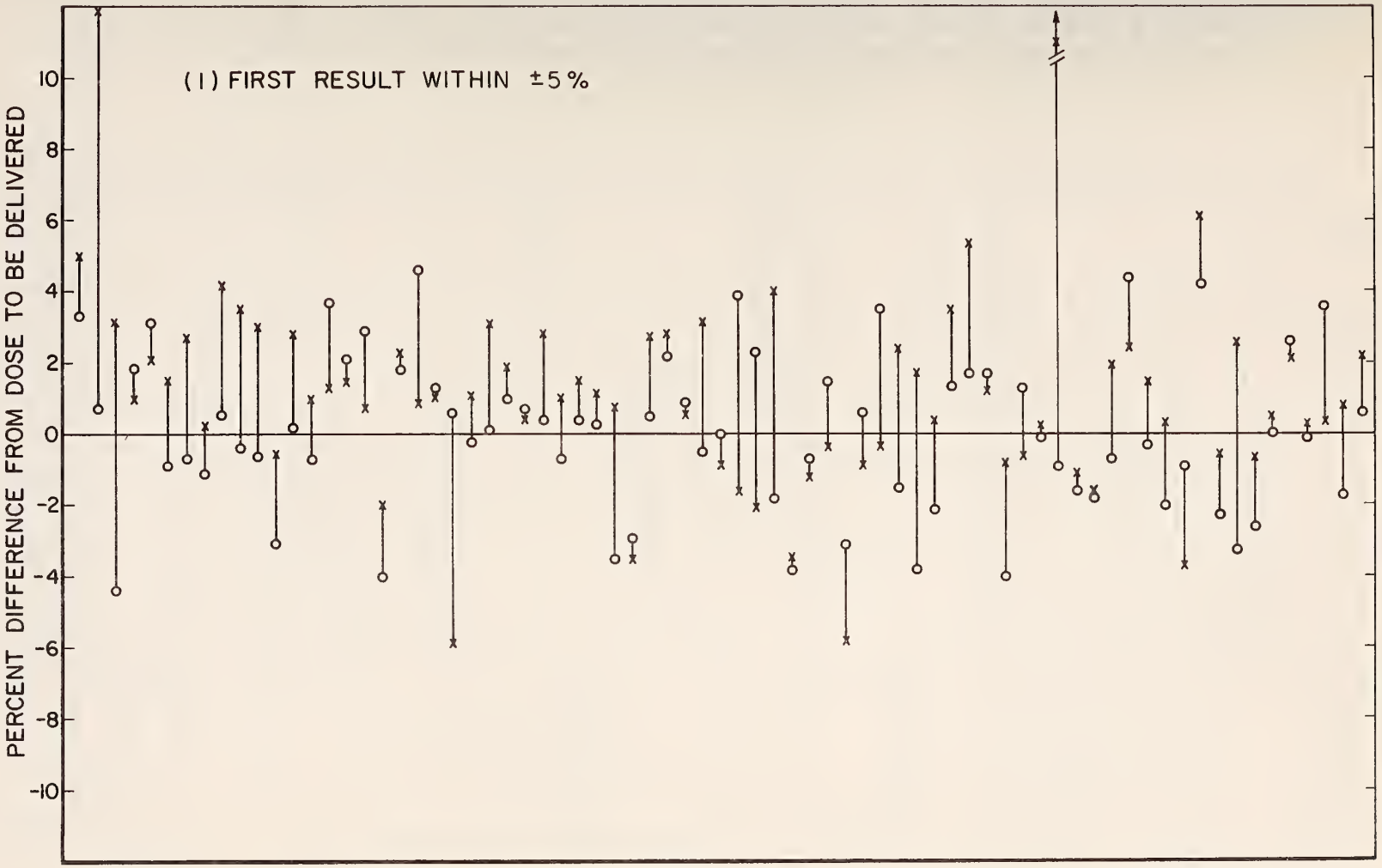

Figure 7A. Comparison of Results from Initial Survey and Re-Survey, Grouped According to Performance in Initial Survey. Part 1, Initial results within ± 5 percent. Circles: initial survey results; x marks: re-survey results.

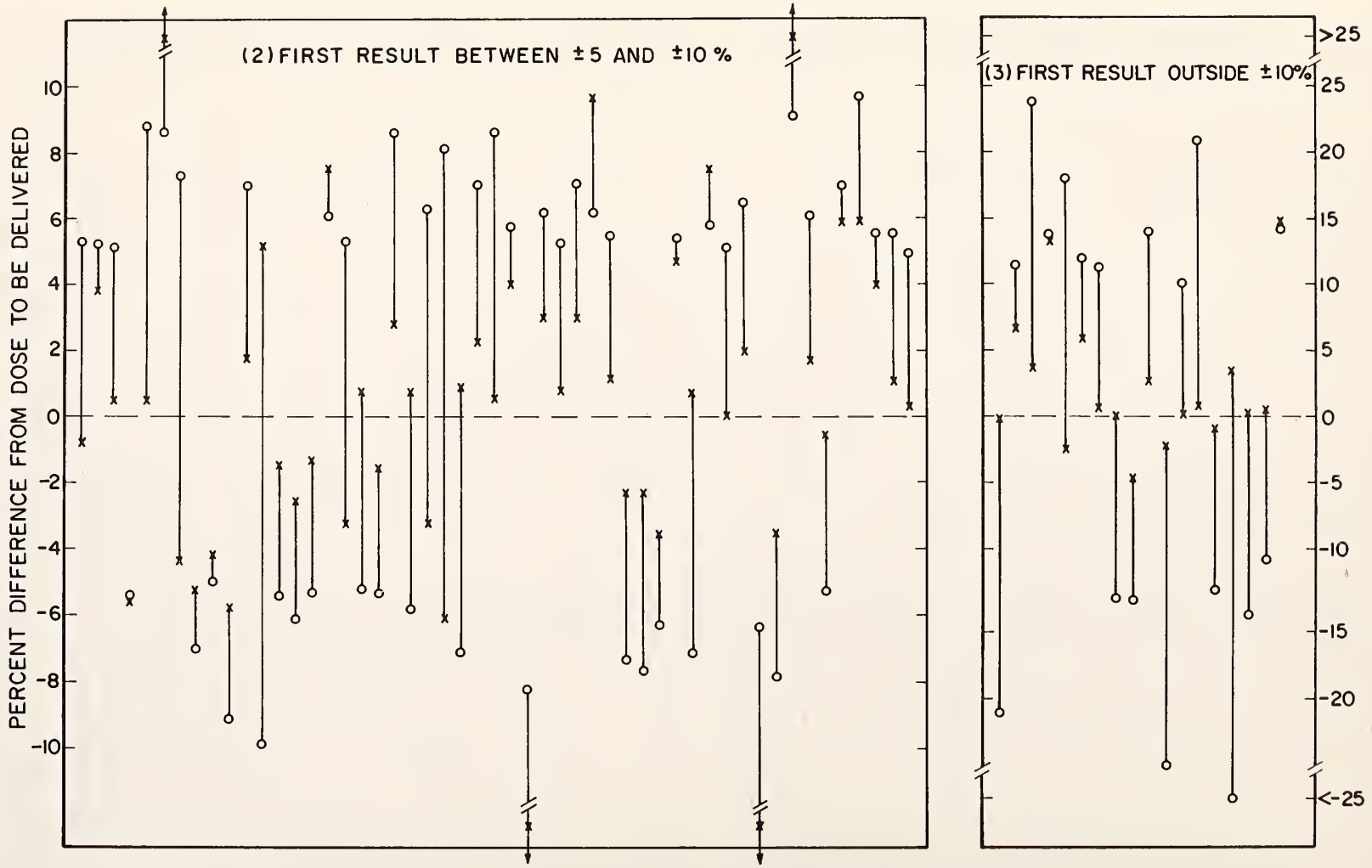

Figure 7B. Comparison of Results from Initial Survey and Re-Survey, Grouped According to Performance in Initial Survey. Parts 2 and 3, Initial Survey results between ± 5 and ± 10 percent and outside of ± 10 percent, respectively. Circles: initial survey results; x marks: re-survey results.

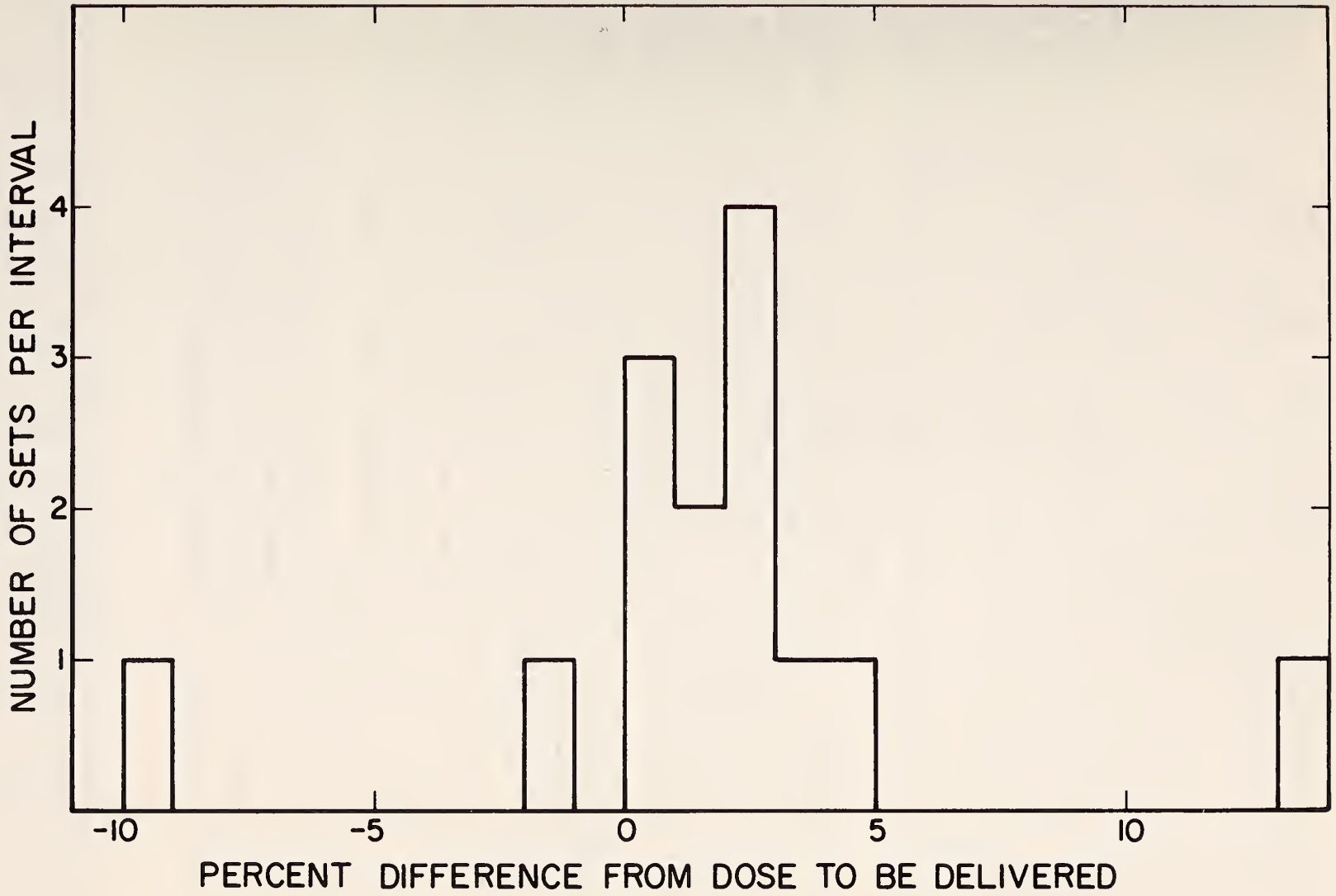

Figure 8. Performance of the Thirteen Participants Selected from among Licensees who did not Participate in the Initial Survey.

malfunctions. There even was a discrepancy that was traced by the participant to an error in the computer output upon which his dose-rate chart had been based. Most of the above errors could also occur during patient irradiation. It should be noted however that the exposure protocol for the dosimeters did not completely reflect the usual clinical setup and therefore a greater incidence of human error was to be expected, especially for individuals who were participating in the survey for the first time.

Of interest also were the methods and factors used by the participants to derive absorbed-dose rate in water from the calibration data. Most participants calibrate in terms of exposure rate in air and use one of the first three methods shown in table 8 to convert to absorbed-dose rate. Examination of some of the early results [2] indicated that a majority of the errors made in this conversion stemmed from a failure to apply one or more of the necessary factors, or from the use of incorrect factors. A full analysis of the results correlated with calibration method is being done by the Bureau of Radiological Health.

6. COMPARISON WITH RESULTS OF OTHERS

In the United States, the only other comprehensive survey somewhat comparable to that carried out by NBS was initiated on an emergency basis by the Nuclear Regulatory Commission (NRC) at a time when the NBS study was more than half completed. In this study, for which the portion comprising mailing of TL dosimeters was patterned after the NBS survey, all U.S. teletherapy users who could not show satisfactory results from a participation in another recognized independent national survey program (such as, e.g., the NBS-BRH voluntary survey here described) were made to participate. A total of 592 units was checked, of which about 64 percent were found to come within 5 percent of the requested dose.* Inasmuch as the results of this study showed a considerable bias in the direction toward delivery of lower doses than those requested, while no such bias was found in our study, it cannot be ruled out that this bias had its origin in the dosimetry system that had to be assembled rather hurriedly. Thus, the overall performance conceivably was better than indicated by the results. In states in which the NRC has inspection responsibilities, the mailed study was followed up by direct inspection and measurements, through which almost all the discrepancies could be satisfactorily resolved.

Preliminary results obtained at the Radiological Physics Center in Houston, in which all but three of the 230 units surveyed by mail were found to have delivered within 5 percent of the requested dose, [4] cannot be considered to have been representative of performance throughout this country. These results were obtained during the first eight months

---

* The result quoted here is for both the states in which the NRC inspects the facilities of all their licensees ("non-agreement states") and for the states in which the state health departments have this function ("agreement states"). Both in the NBS and the NRC studies there was no significant difference in the performance of teletherapy users in the two categories of states. The NRC results quoted here are for both categories combined. The data for the non-agreement states were reported by Dicey et al.[3] The data for the agreement states are not as yet generally available.

of a continuing survey of institutions involved in certain interinstitutional clinical trials. The institutions had been visited by physicists from the Center prior to being surveyed by mail--although in some instances not for some time. Earlier results obtained by this Center in personal visits to 174 institutions involved in clinical trials showed that of the 352 teletherapy units checked and of the 768 associated tumor-dose prescription protocols reviewed 88 percent were within 5 percent of the prescribed tumor dose. [5] In our own mailed TL dosimetry study, we found that 83 percent of the 906 units surveyed delivered doses to a water phantom that were within 5 percent of the requested dose. If one assumes that institutions involved in clinical trials are representative of all institutions administering teletherapy, this result would indicate that it is possible to obtain information from mailed TL dosimetry studies that correlates with that obtained in actual visits to the institutions.

Results obtained from a cross section of national institutions by a secondary-standard dosimetry laboratory are also available from India. [6] There, 19 of the 32 teletherapy units (59%) came within 5 percent of the requested dose, and four had results differing by more than 10 percent. A continuing international survey is being conducted by the International Atomic Energy Agency in conjunction with the World Health Organization. The results for the years 1970 - 1975 [7] covering 417 measurements (including follow-ups on some of the participants) showed about 63 percent of the delivered doses to be within 5 percent of the requested dose and 15 percent to differ by more than 10 percent.

7. ACKNOWLEDGEMENT

The authors wish to express their appreciation to Mr. J. M. Cameron, chief, Office of Measurement Services (now retired) and to Dr. H. H. Ku, chief, Statistical Engineering Division, for their assistance with the analysis of the uncertainties in the NBS method for determining absorbed dose from dosimeter response.

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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

Table 1

Initial Inquiry Letter

As a part of a program of testing the National Measurement System, the National Bureau of Standards, in cooperation with the Bureau of Radiological Health, is undertaking a study to determine whether the NBS methods for making dosimetry standards available are adequate or need to be improved. For this purpose, we are conducting a test of the accuracy with which a prescribed dose of cobalt-60 gamma radiation is delivered to a specified point in a water phantom. This test will involve radiotherapy departments throughout the United States.

You are among those selected on a random basis for participation in this study, which will be performed at no cost to the participants. If you are willing to participate, several thermoluminescence dosimeters will be mailed to you for irradiation and subsequent return to us for evaluation. We will then inform you of our dose interpretation for the readings on the dosimeters, which is capable of revealing discrepancies of five percent or more. While our study cannot be considered in any way to take the place of a regular calibration of your unit, we believe that the information gained will be of value to you and will provide some compensation for your efforts.

Please indicate on the enclosed form whether or not you are willing to participate and, if you are, to whom all future correspondence should be directed, including the report of the results. Return the completed form in the enclosed stamped and addressed envelope. The performance of the individual participants in this study will not be disclosed by us to anyone, and only anonymous statistical compilations of the results will be reported to the Bureau of Radiological Health or otherwise made public.

Sincerely,

R. Loevinger

R. Loevinger
Chief, Dosimetry Section
Center for Radiation Research

NOTE: A SELF-ADDRESSED STAMPED ENVELOPE IS ENCLOSED.

Table 2

Participation Questionnaire

I am willing to participate in the NBS ^{60}Co teletherapy dosimetry-assurance study. I am not

(Please strike out the phrase that does not apply.)

I have _____ ^{60}Co teletherapy units.
how many

Name and address for all future communications (please print or type):

Name: _____

Organization: _____

Street Address: _____

_____

_____

Telephone No. (Area Code) _____

_____
(Date)

_____
(Signature)

Note: If there are any times during the next few months when you would be unable to participate because of vacations or the like, please indicate.

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Table 3

Follow-up Inquiry Letter

We have not received your answer to our inquiry regarding your interest in cooperating in a cobalt-60 dosimetry survey. We are anxious to include in our survey a large fraction of the groups that we initially approached. We had selected these groups on a random basis from among all those owning cobalt-60 teletherapy equipment. If a large number of those approached were not to participate, the validity of the conclusions drawn from our survey results would suffer.

In case you meant to participate but happened not to return the first questionnaire, please mail the one enclosed with this note, if possible some time before For your convenience, we also are sending you a self-addressed envelope that needs no stamp.

Sincerely,

Margarete Ehrlich, Physicist
Dosimetry Section
Center for Radiation Research

Enclosures

U.S. DEPARTMENT OF COMMERCE
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Table 4

Announcement of Dosimeter Mailing

Thank you for letting us know that you are willing to participate in our comparison of dose calibrations of ^{60}Co gamma-ray therapy units. We should like to reemphasize that this study will be carried out free of charge, that it is confidential, and that only anonymous statistical compilations of the results will be made public, but that each participant will be notified of his own results.

On or about one set each of six dosimeters per $^{Co}60$ teletherapy unit will be mailed to you. The dosimeters consist of CaF_2:Mn thermoluminescence material in glass bulbs, contained in black plastic blocks. Five of the six dosimeters are for irradiation, one is a control that should be kept away from radiation at all times. Please do not open the black blocks. The bulbs inside are light-sensitive and fragile. Along with the dosimeters, we are going to mail you

instructions;
an exposure-information form;
a return-address label requiring no postage; and
a copy of this letter.

Please carry out the irradiations within three workdays of the receipt of the dosimeters. Follow the instructions in detail and return all dosimeters and the completed exposure-information form in the original mailing carton. Also, note that for the study to yield realistic results the dosimeter irradiations should be performed under conditions duplicating as closely as possible the routine patient irradiations and the individuals carrying out the irradiations should be those routinely involved in patient set-up and treatment.

We may not be able to evaluate the doses received by dosimeters reaching us after

Sincerely,

Margarete Ehrlich, Physicist
Dosimetry Section
Center for Radiation Research
telephone: (301) 921-2366 or 2361

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

Table 5

Instructions for Irradiating the Dosimeters

1- Please carry out the irradiations as soon as possible after the dosimeters arrive, if possible mailing them back within three working days.

2- When you are ready for the exposures, remove all six black plastic dosimeter blocks from the mailing carton. (Five of these are for irradiation, one is a control.) Take the mailing carton and one block at a time into the treatment room. Turn the carton on its side, place it on top of your treatment table, and center the block, screw heads up, on the carton.

3- Use your normal treatment distance unless it is smaller than 50 cm, in which case use a distance of 50 cm. If you normally measure your distance to the surface ("SSD Technique"), follow the instructions in 3.1. If you normally measure distance to the tumor ("SAD Technique"), follow the instructions in 3.2.

Please note that while the exposures are not to be made with the dosimeter blocks in a phantom, the absorbed-dose rate and the exposure time should be computed as if the dosimeters (located in the plane of the crack in the block) were at a depth of 1 cm in a large water phantom.

Also note that for the study to yield realistic results the dosimeter irradiations should be performed under conditions duplicating as closely as possible the routine patient irradiations and the individuals carrying out the irradiations should be those routinely involved in patient set-up and treatment.

PLEASE DO NOT ADD ANY PHANTOM MATERIAL.

Table 5, continued

Instructions for Irradiation the Dosimeters, cont.

3.1 SSD Technique (See Sketch 3.1)

a- Measure the source-surface distance to the proximal surface of the block.

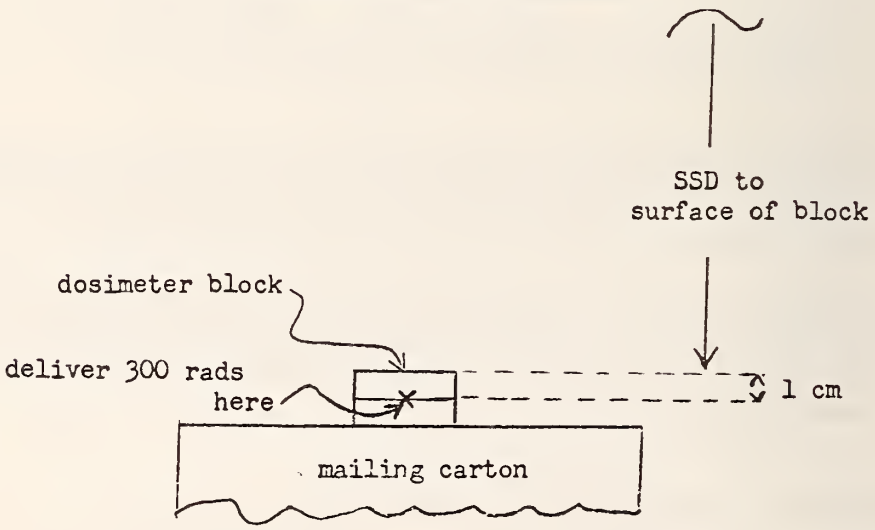
b-Set the field size at the measured distance to 10 cm x 10 cm.

c- Set the timer to deliver 300 rads calculated at a 1 cm depth in water (soft tissue*) and expose.

d- Proceed with step 4.

SKETCH 3.1, SSD Technique

SKETCH 3.1, SSD Technique



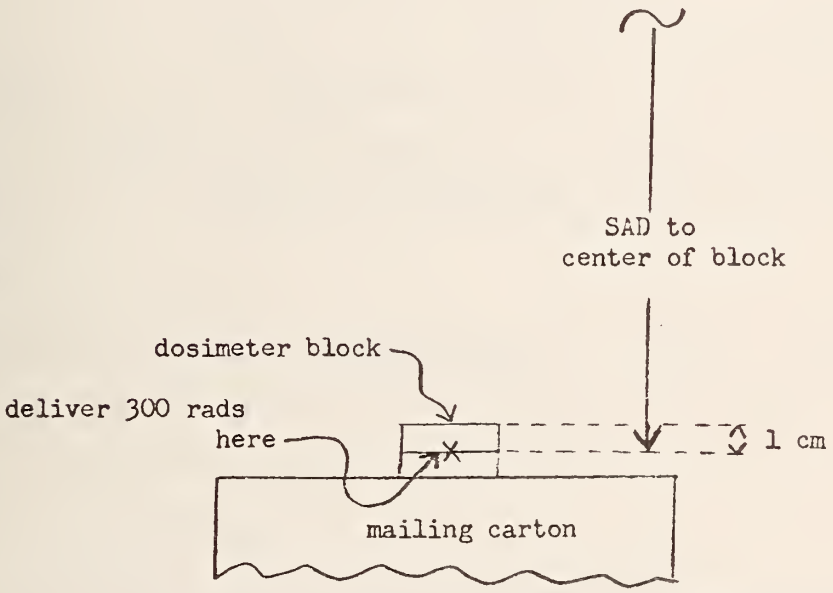
*For this study, absorbed dose in water and in soft tissue will be assumed to be the same.

Instructions for Irradiating the Dosimeters, cont.

3.2 SAD Technique (See Sketch 3.2)

a- Measure the source-axis (or source-tumor) distance to the center of the block (where the crack is), i.e., 1 cm below the surface.
b- Set the field size at the measured distance to 10 cm x 10 cm.
c- Set the timer to deliver 300 rads calculated at a 1 cm depth in water (soft tissue*) and expose.
d- Proceed with step 4.

SKETCH 3.2, SAD Technique



4- Irradiate five of the six blocks identically. One block must remain unexposed to serve as a control.

5- Fill out the Irradiation-Information Form completely(three pages). If possible, have your physicist complete pages 2 and 3. The information on these pages would enable us to determine how absorbed-dose rate and exposure time for the irradiation of the NBS dosimeters were obtained.

6- Place all six dosimeter blocks and the exposure-information form back into the mailing carton and return the carton to us by mail, using the enclosed address label which requires no postage.

*For this study, absorbed dose in water and in soft tissue will be assumed to be the same.

Table 6

IRRADIATION INFORMATION FORM

(TO BE RETURNED WITH THE DOSIMETERS)

I. Please supply all pertinent information on this page; then proceed to pages 2 and 3. The information on this page is essential to the interpretation of the dosimeter readings; therefore this page should be returned with the dosimeters. Pages 2 and 3 may be returned at a later date.

Date of irradiation:_____

Time of day of irradiation:_____

Distance to dosimeter-block surface, SSD = _____cm or

Distance to point at which 300 rads delivered, SAD = _____cm.

Field size at specified distance _____cm x _____cm.

Irradiation time (actual time, not corrected timer setting): _____min

_____sec.

Dosimeters exposed by _____
(name, title)

* * *

This page was filled out by_____
(name, title)

on _____
(date)

PLEASE DO NOT FORGET TO RETURN THE PACKAGE CERTIFIED MAIL

AND TO OBTAIN AND SAFE-KEEP THE CERTIFIED MAIL NUMBER

II. Please supply all pertinent information on this and the next page, if possible. If there is a significant difference between our dose interpretation and the dose that you believe you delivered to the dosimeters, the information on these pages will enable us to determine if this difference is due to calculation error.

1- Type of machine mount (circle one): Vertical Isocentric

2- Calibration

The unit was last calibrated (fill in whichever is applicable):

2.1 in terms of exposure rate (no phantom) for a field size of ____cm x ____cm. at a distance of ____cm; exposure rate:____R/min on _____(date);

2.2 in terms of exposure rate in a large phantom[1] for a field size of ____cm x ____cm, at a SSD of ____cm, at a depth of ____cm; exposure rate:____R/min on _____(date);

2.3 in terms of absorbed-dose rate in an equilibrium mass of water[2] ("miniphantom") for a field size of ____cm x ____cm, at a distance of ____cm to the center of the miniphantom; absorbed-dose rate:____rad/min on _____(date);

2.4 in terms of absorbed-dose rate in a large phantom[1] for a field size of ____cm x ____cm, at a SSD of _____cm, at a depth of ____cm; absorbed-dose rate:____rad/min on _____(date).

2.5 other (specify):

3- Absorbed-Dose Computation

3.1 Factors used

Please note: Not all of the factors listed can be used in any one calculation. Do not specify values for factors that you did not use.

3.1.1 Source-decay correction for time elapsed between calibration and irradiation date:_____

---

[1]Please specify phantom material (check one or write in):

Water Polystyrene Lucite Other:

[2]For ^{60}Co radiation, a sphere of water of 0.5cm radius is an equilibrium mass, i.e., just large enough for electronic equilibrium.

3.1 Factors used, continued

3.1.2 Exposure-to-absorbed-dose conversion factors

F factor:_____

f factor:_____

C_λ :_____

attenuation correction:_____
(cap correction, A_C, A_{eq})

displacement correction:_____

others:_____

3.1.3 Inverse-square correction from_____cm to _____cm: _____

3.1.4 Tissue/air ratio:_____

3.1.5 (Back) scatter factor, i.e., buildup factor due to scatter in large phantom:_____

3.1.6 Percent depth dose:_____

3.1.7 Others (explain):

3.2 Result of computation of absorbed-dose rate for use in irradiation of the set of NBS dosimeter blocks:

Absorbed-dose rate at 1 cm depth in large water phantom:_____rad/min.

* * *

Pages 2 and 3 of this form filled out by _____on_____
(name, title) (date)

Table 7

Text of Report Sent to Participants

ACCURACY WITH WHICH A PRESCRIBED ABSORBED DOSE

OF COBALT-60 GAMMA RADIATION IS DELIVERED TO A SPECIFIED POINT IN WATER

Report on the Performance of the

Participants that were sent Dosimeters in

by

Margarete Ehrlich and Christopher Soares

Dosimetry Section, Center for Radiation Research

National Bureau of Standards

This study was undertaken under Interagency Agreement FDA-IAG 74-41 (0), Modification No. 1, between the National Bureau of Standards and the Food and Drug Administration, Bureau of Radiological Health.

Attached are the results and some pertinent background data for the survey involving participants (sets). The following information is supplied.

Table 1a* - A list of the major methods in use for computing absorbed-dose rate at a depth of 1 cm in a water phantom from the calibration data of a cobalt-60 gamma-ray source referred to the date of irradiation. NBS used eq. (3) in the computation of absorbed-dose rate from exposure parameters for the NBS cobalt-60 calibration source. For checking the participants' computed doses, NBS used the numerical values listed in Table 1b for the pertinent parameters and constants.

Table 1b*- A list of symbols used in Table 1a and of values for pertinent parameters and constants.

Table 2 - This table contains the following information:

(a) A list of the individual absorbed-dose interpretations obtained for all irradiated dosimeters, the average dose interpretation for each participant, and the percent difference, Δ, between the NBS dose interpretation and the dose to be delivered (300 rads in water, unless otherwise indicated). Note that the red arrow points to the results of the participant to whom this report is being mailed.

Absorbed dose was computed from the readings of the dosimeters irradiated by the participants after suitable corrections for differences in individual dosimeter sensitivity, and for fading. Differences Δ outside the NBS overall error limits (see below) are an indication of wrong source calibration or of wrong delivery parameters (such as, faulty positioning, wrong field size, wrong timer setting, faulty timer) or of improper computation (such as wrong equations, wrong values for the parameters and constants, errors in arithmetic).

---

* In this paper shown as tables 8 and 9.

(b) A list of the doses computed by NBS from the information supplied by the participants, and of the methods according to which the computations were carried out. A discrepancy between the computed dose and the dose to be delivered (300 rads in water, unless otherwise indicated) is an indication of improper computation.

Figure 1 - This is a histogram of the percent difference, Δ, between the average NBS dose interpretation obtained from all the individual interpretations for a participant, and the dose to be delivered (300 rads).

Details on the dosimetry system used and on the method of dose evaluation will be published in the future, along with a review of typical survey results. At this point, it suffices to state the following results of our error analysis:

1 - The bound for the total systematic error of our method is estimated to be $\sim 2\frac{1}{2}$ percent.

2 - The bound for the total random error in our dose interpretation is estimated to be

a - ~ 3 percent for readings on a single dosimeter;

b - $\sim 1\frac{1}{2}$ percent for the average of readings on five dosimeters.

3 - Therefore, the overall error in the average NBS dose interpretation for readings on five dosimeters is estimated to be less than 4 percent.

Margarete Ehrlich

Date

Christopher Soares

Table 8

Method for Computing Absorbed-Dose Rate at a

Depth of 1 cm in a Water Phantom

Method Number	Source Calibrated for	Method for computing $D_{\text{at 1cm}}$
1	$\dot{X}$ at SSD[1] (no phantom)	(a) $(\dot{X})[SSD/(SSD+0.5)]^2(f)(A)(BSF)(\%DD)_{1\ cm}$ (b) $(\dot{X})[SSD/(SSD+1)]^2(f)(A)(TAR)_{1\ cm}$
2	$\dot{X}$ at SSD + 0.5cm (no phantom)	$(\dot{X})(f)(A)(BSF)(\%DD)_{1\ cm}$
3	$\dot{X}$ at SAD (no phantom)	$(\dot{X})(f)(A)(TAR)_{1\ cm}$
4	$\dot{X}$ at depth d cm (in phantom)	$(\dot{X})(f)(A)(\%DD)_{1cm}/(\%DD)_{d\ cm}$
5	$\dot{D}$ at center of water miniphantom,[2] positioned at SSD	(a) $(\dot{D})[SSD/(SSD+0.5)]^2(BSF)(\%DD)_{1\ cm}$ (b) $(\dot{D})[SSD/(SSD+1)]^2(TAR)_{1\ cm}$
6	$\dot{D}$ at center of water miniphantom, positioned at SSD + 0.5 cm	(a) $(\dot{D})(BSF)(\%DD)_{1\ cm}$ (b) $(\dot{D})[(SSD+0.5)/(SSD+1)]^2(TAR)_{1\ cm}$
7	$\dot{D}$ at center of water miniphantom, positioned at SAD	$(\dot{D})(TAR)_{1\ cm}$
8	$\dot{D}$ at depth d cm in phantom	$(\dot{D})(\%DD)_{1\ cm}/(\%DD)_{d\ cm}$

[1] All distances are in cm.

[2] For ^{60}Co gamma rays, a water sphere of 0.5 cm radius is a "miniphantom", i.e., a phantom just large enough for establishing electronic equilibrium at its center.

Table 9

Parameters and Constants Entering Into

Absorbed-Dose Computations

Symbol	Quantity	Value and source, where applicable
$\dot{X}$	exposure rate	--
$\dot{D}$	absorbed-dose rate	--
SSD	source-to-surface distance	--
SAD	source-to-axis distance	--
f	$(\dot{D})_{water}/(\dot{X})_{air}$, obtained under electron equilibrium conditions	0.965,[1] ICRU[2]
A	attenuation correction, cap correction, etc.	0.985, Johns and Cunningham[3]
F	(f)(A)	--
BSF	(back-)scatter factor	BJR Supplement[4]
%DD	percent depth dose	BJR Supplement[4]
TAR	tissue/air ratio	BJR Supplement[5]

(1) **We use the value for water in our calculations for this survey. For soft tissue, the corresponding ratio is 0.957.**

(2) Table IV.1, ICRU Report 10d(NBS HB 87), 1963.

(3) Table IX.1, p. 274, The Physics of Radiology, Third Edition, 1969.

(4) Tables 6.1 through 6.4, BJR Supplement No. 11, 1972.

(5) Table 6.5, BJR Supplement No. 11, 1972.

Table 10

Uncertainties in NBS Method of Determining
Absorbed Dose from Dosimeter Response

Systematic Uncertainty		
NBS exposure calibration of Co-60 Gamma-ray source		0.7%
Uncertainty in dosimeter calibration		0.7%
Uncertainty in dosimeter fading correction		1.0%
Total		2.4%
Random Uncertainty		
Reproducibility of individual dosimeter response (3S)	2.4%	
Correction for sensitivity variation between dosimeters	2.4%	
Total for corrected individual dosimeter response	3.4%	
Total for average corrected response of five dosimeters		1.5%
Total Uncertainty in dose interpretation from average of five dosimeters		∿ 4.0%

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15. SUPPLEMENTARY NOTES

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

Between September 1974 and December 1977 the National Bureau of Standards, in cooperation with the Bureau of Radiological Health, performed a study of the accuracy with which a prescribed absorbed dose of cobalt-60 gamma radiation is delivered to a specified point in a water phantom. Approximately two-thirds of the cobalt-60 teletherapy units in the U.S. were surveyed by mail, using a rugged thermoluminescence dosimetry system. The dose given by participants was evaluated from dosimeter response, and information supplied by participants was used to check their computations of the dose delivered. In this nationwide study, 83 percent of the units surveyed yielded dose interpretations within 5 percent of the requested dose, 13 percent yielded differences between 5 and 10 percent, and 4 percent of the dose interpretations differed by more than 10 percent from the dose requested. Sources of discrepancies are discussed, and the results of this survey are compared with those of other dosimetry surveys.

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

Absorbed dose; cobalt-60 gamma radiation; computation check; dose interpretation; mailings; survey; teletherapy; thermoluminescence dosimeters; water phantom

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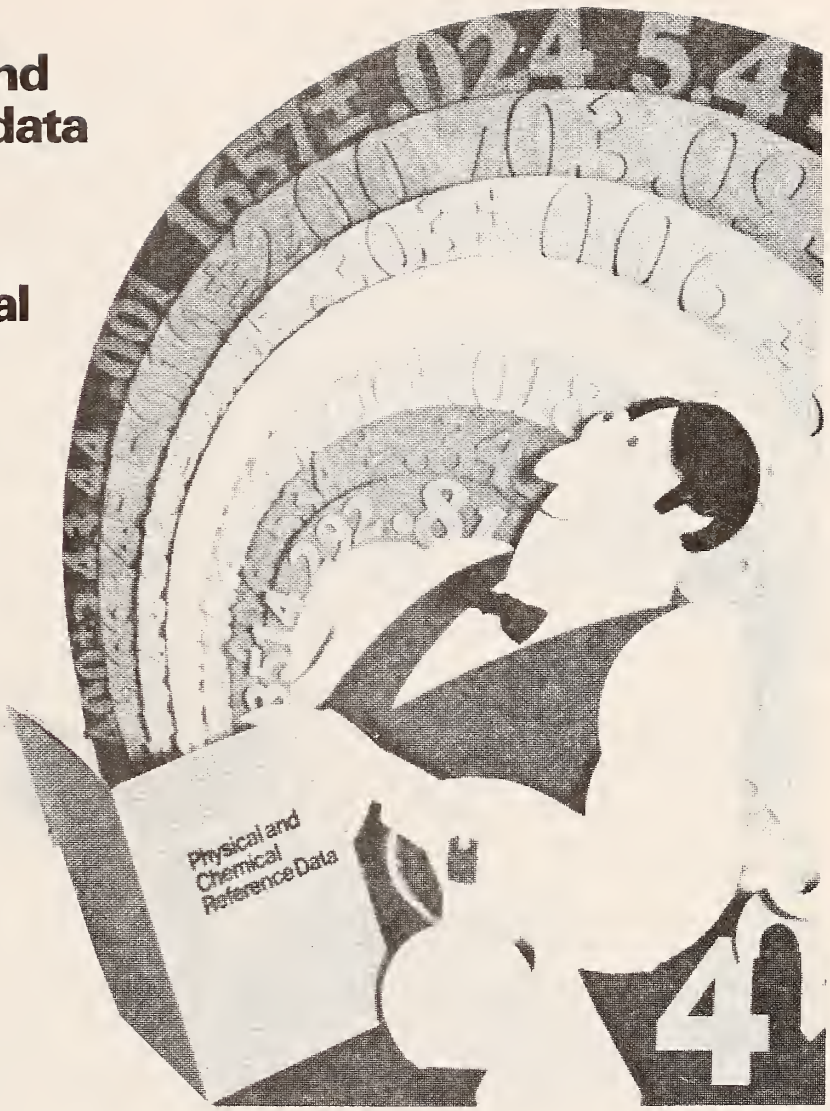

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JOURNAL OF RESEARCH—The Journal of Research of the National Bureau of Standards reports NBS research and development in those disciplines of the physical and engineering sciences in which the Bureau is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology, and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Bureau's technical and scientific programs. As a special service to subscribers each issue contains complete citations to all recent NBS publications in NBS and non-NBS media. Issued six times a year. Annual subscription: domestic $17.00; foreign $21.25. Single copy, $3.00 domestic; $3.75 foreign.

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DIMENSIONS/NBS

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NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N.W., Wash., D.C. 20056.

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