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**THE ESTABLISHMENT
AND UTILIZATION
OF FILM DOSIMETER
PERFORMANCE CRITERIA**

C. M. UNRUH, H. V. LARSON,
T. M. BEETLE AND A. R. KEENE

SEPTEMBER, 1967

**AEC RESEARCH &
DEVELOPMENT REPORT**

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By

C. M. Unruh, H. V. Larson,
T. M. Beetle and A. R. Keene

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Pacific Northwest Laboratory
Battelle Memorial Institute
Richland, Washington

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THE ESTABLISHMENT AND UTILIZATION OF FILM DOSIMETER PERFORMANCE CRITERIA

C. M. Unruh, H. V. Larson, T. M. Beetle, and A. R. Keene

I. INTRODUCTION

Film badge dosimeters are established as the commonly used dosimeters for measuring radiation dose to personnel working in a wide variety of radiation exposure environments. The increasing use of radionuclides and radiation generating equipment in industry, medicine, education and research and the relatively low capital cost required has resulted in the establishment of many film dosimeter processing companies. At least 15 commercial firms offering film dosimeter processing and evaluation service are now in business. An even greater number of Atomic Energy Commission, AEC prime contractors, and military installations operate their own film dosimeter services.

The commercial film dosimeter processing business is highly competitive, where well qualified firms compete against some firms who may not measure up to what are considered adequate minimum standards of performance. Customers tend to accept the service provided them and are generally inclined to contract personnel film dosimeter processing to the lowest bidder. This situation may lead to sub par performance by film dosimeter processors, resulting in dosimeter processing and evaluation service not fully meeting the quality of performance that can be obtained with reasonable attention to technical and operational details.

The AEC recognized these conditions many years ago and published in the Federal Register, on September 4, 1963, a notice regarding the need for the establishment of a Film Dosimetry Calibration Laboratory (Appendix A). Included in this notice was a table providing some interim film dosimeter performance criteria. These criteria were based on recommendations developed in meetings attended by a number of health

physicists involved in providing personnel film dosimetry services at AEC installations. The radiation energy ranges, dose ranges, and dosimeter performance levels proposed were generally determined on the basis of extensive experience and professional expert judgment. They served as a good, general indication of the performance level the technology had achieved in 1963. No method of comparing actual performance directly with these AEC recommended interim performance criteria was ever established. Consequently, these performance criteria as such, have not been effective in upgrading or in evaluating the performance levels of film dosimeter processors.

Since 1955, at least seven studies have considered the evaluation of film dosimeter processor performance or the establishment of film dosimeter performance criteria⁽¹⁻⁷⁾. The National Sanitation Foundation (NSF) has provided a basis for the film dosimeter processors to meet together and to establish self-imposed performance standards. These activities have been in progress for the past several years. The performance standards developed in the National Sanitation Foundation program are stated in their report to be "comparable with the interim control limits proposed by the AEC in 1963. This is not to suggest that the control limits proposed either by the Foundation or the AEC represent satisfactory performance in personnel dosimetry. The control limits reflect only the present level of performance of film badge services".⁽⁷⁾ The AEC concluded that the NSF objectives appeared to be consistent with AEC objectives, but without further study, the AEC was not in a position to judge the adequacy of the NSF program relative to the needs of the Commission. Consequently, the Commission requested Battelle-Northwest (a division of the Battelle Memorial Institute), who operates the AEC's Pacific Northwest Laboratory, to conduct a study that would determine film dosimeter performance criteria, and to form the basis that could be used for the establishment of a Film Dosimetry Calibration Laboratory, if the need for such a Laboratory was shown by the study.

II. CONCLUSIONS

Results of this study are as follows:

- Reasonable criteria to define acceptable levels of performance with respect to variance and bias can be established and administered.
- Excessive bias and variance exist among film dosimeter processors. These are found in all groups participating in the test irradiation study; commercial firms, AEC laboratories and military installations.
- A program that would provide an assessment of the quality of film processing services appears to be desirable. Three alternative lines of action could be considered, and under any one of these, a degree of achievement of this assessment would be obtained.
 - a. A Film Dosimeter Processors Evaluation Program administered on a required basis would afford a high degree of assurance of sustained adequate performance by commercial and AEC groups providing film dosimetry service.
 - b. A Film Dosimeter Processors Evaluation Program administered on a voluntary basis would provide most of the improvements of, but somewhat less overall assurance than, a full regulatory program.
 - c. A central Calibration Laboratory for film dosimeter processors would essentially eliminate the biases revealed by this study. This would yield important benefits even if no processor evaluation functions were included.

III. OBJECTIVES

This study had as its overall objective the development of a system to provide users of film processing services and regulatory agencies with a means of assuring that adequate film dosimetry is being provided. The specific objectives of the study were:

- The development of practical and meaningful film dosimeter performance criteria.
- The determination of the need for establishing a Film Dosimeter Evaluation Program to identify processors who are providing adequate technical service.
- The development of a system of administrative and technical procedures for implementing the Evaluation Program if the need is indicated.
- The identification of facilities, equipment, staff and costs for the establishment and operation of a Film Dosimetry Calibration Laboratory in which to conduct the Evaluation Program if the Program is deemed necessary or desirable.

IV. APPROACH USED IN STUDY

DEVELOPMENT OF FILM DOSIMETER PERFORMANCE CRITERIA

There are a number of approaches that may be used to develop film dosimeter performance criteria. Several of these were considered prior to the selection of the basic approach used in this study.

First, the study of fundamental film performance data collected by conducting controlled physics type experiments could be used as a basis for establishing performance criteria. This method of study considers all factors relating dosimeter film darkening, radiation type, energy and dose, dosimeter design, the effect of environmental parameters and processing parameters on the film dosimeter performance and the use of different calibration, processing and evaluation techniques. Initially, it was contemplated that this approach would be used to derive the performance criteria. It became quickly apparent that although the approach is sound for a controlled physics laboratory operation, it is unrealistic for use in developing practical and useful film dosimeter criteria.

A second approach considered was the selection of a single film dosimeter processor judged to operate in a fully satisfactory manner and having fully adequate equipment. Once these judgments as to the capabilities of the processor were made, a statistical analysis of this level of performance could be used as a basis for establishing performance criteria. While this approach provides criteria that can be met, it does not consider the variety of operational methods and processing equipment that may be used by various processors. It tends to place undue emphasis on a given set of operational methods and on the procurement of specific operating equipment. This method was discarded from further consideration because it could lead to a rigid and generally costly method of processor operations.

A third possible method was to conduct an extensive performance evaluation study of all the industry and to evaluate the observed average performance results. The average performance would then be used to derive the performance criteria. While this method has some merit, it does not yield performance criteria based on the level of film dosimetry technology that can be practically attained. A few poor performers tend to distort the average performance by excessive amounts. This averaging technique tends to provide criteria weighted toward inferior performance.

A fourth method of criteria development is to select a group of processors comprised of a reasonable percentage of the processors and to use their observed performance in a test irradiation program as a basis for criteria establishment. In this group it is necessary to select only processors judged to have adequate equipment, and then to use adequate methods of operation. These judgments of adequacy are subjective and based on the past experience of those making the selection. This method of performance criteria development was selected for use in this study. It provides performance criteria that can be reasonably attained with a reasonable complement of equipment, personnel and operating methods. Also, it provides the best measure of what is technologically feasible and practical at the current time with processing equipment and methods in general use. Although many variations pertaining to the size of the processor group selected can be made, the performance criteria developed does not change substantially with the addition or deletion of a few to the selected group of processors.

The test irradiation program was performed to:

- Estimate the quality of film dosimeter performance currently achieved
- Establish the basis for the development of industry-wide performance criteria
- Determine the effect of a given set of performance criteria on film dosimeter processors.

For the test irradiation program, each test film dosimeter was clearly identified, and the type of each radiation exposure was known by each processor. Secret or blind tests of processing capability were not conducted. It is likely, therefore, that the participants provided their best effort in processing and evaluating each test dosimeter. This provided a measure of the quality of performance which could be currently provided by a processor with the equipment and methods now at hand.

The number of dosimeters required for the test irradiation program was determined by examining Hanford personnel film badge dosimeter data for the past 14 years. A test irradiation program was devised to provide equally precise estimates of variance at each dose level chosen; however, for practical reasons, a few nominal reductions in the program at some dose levels were made without appreciable reduction in reliability. A total of 218 dosimeters were required for each processor participating in the complete test program. Some processors did not offer service in all of the radiation categories and, hence, chose to participate only in part of the test irradiation program.

The types of radiation used in the test irradiation program were chosen to simulate those encountered by people exposed to radiation in the course of their employment or education. Four radiation categories photon, beta, neutron and mixtures--were established to encompass these radiations. Four subcategories were used for photon radiations to cover three energy ranges and a high dose range. Neutron subcategories of fast and thermal were used. Mixtures of photon and beta radiations and high (200 keV to 3 MeV) and low energy (15 keV and 50 keV) photons were used for mixed radiation exposures. Other categories, such as fast neutron and photon or low energy photon and beta radiation were considered but were not established because 1) they are seldom encountered,

2) the mixing does not substantially effect the dosimeter evaluation of either component, or 3) the categories tested provided sufficient basis to assure reasonable performance for the mixtures. The high energy particle and photon radiations from accelerators were considered to be beyond the scope of this study and were not considered.

Gamma radiations from radium were used for the relatively low dose level exposures. The multi-energy spectrum of the radium gamma radiation was taken to be the most practical representation of the radiation energies encountered in facilities utilizing many radionuclide sources or X-ray machines with output energies between 200 keV and 1 MeV. ^{60}Co was used for the high dose level exposures. The high energy ^{60}Co irradiations were taken to be a suitable representation of the photon radiations that could be encountered in a high dose accidental exposure. It was impractical to use radium for these high dose level exposures because of the long exposure time required or the short distances of the exposure for sources of only 0.5 Ci. Heavily filtered X-rays, at energy levels of 170 and 100 keV, were used to simulate exposure that might be received by medical staffs in providing diagnostic and medical treatment to patients. Monoenergetic X-rays from a K-fluorescent X-ray source at about 17 keV (zirconium radiator) were used to simulate very low energy X-rays or scattered radiation exposures. Beta radiation exposures were obtained from polished uranium metal slabs or ^{90}Sr sources. Neutron exposures were obtained from a plutonium-beryllium neutron source exposed in air for fast neutrons and well moderated by graphite in a sigma pile for thermal neutrons. To evaluate the capability of dosimeter processors to interpret exposures to mixed radiations, some dosimeters were exposed to equal doses of radium gamma and uranium beta radiation while others were exposed to equal doses of radium gamma and 17 keV K-fluorescent X-ray radiations.

Expert judgment was utilized to identify technically sound processors whose observed performance was subsequently analyzed as a basis for derivation of the performance criteria presented. The judgment was used to identify, prior to the irradiation tests, five processors providing service in each radiation category whose methods and equipment were judged to have good capability for performing film dosimeter processing and evaluation. Processors from both private industry and from the AEC complex were included in this group of five. The data from these five processors were analyzed and performance criteria were calculated from this data analysis to assure a high probability that two of these five processors always would meet the performance criteria so long as their methods are not changed significantly. The other three processors would have only a slight chance of failing to meet the criteria on any single test. The data from all processors were used to determine the effects of the criteria on the industry. The suggested method of application of the performance criteria, which is discussed in detail in Appendix B and C is designed to assure that all processors with reasonable technical capabilities can meet or exceed the established criteria.

DETERMINATION OF THE NEED FOR A FILM DOSIMETER EVALUATION PROGRAM

The basis for determining the need of a film dosimeter evaluation program was an analysis of the results of the test irradiation program. The principal factors in this consideration were the determination of the bias and the variance commonly encountered in dosimeter film processing laboratories today. If both bias and variance were well controlled there would be little justification for a dosimeter evaluation program.

Other considerations, in addition to the actual performance of film processors include the need to demonstrate from time to time that performance is adequate.

Technical experts of the AEC, the Federal Radiation Council and the National Committee on Radiation Protection and Measurements were consulted on a variety of aspects relating to the need for adequate personnel film dosimeter evaluations.

DISCUSSIONS WITH OTHER LABORATORIES, PROCESSORS AND AGENCIES

The actual feasibility of establishing and implementing an evaluation program was determined from the experience gained in conducting the test irradiation program, from firsthand experience in operating similar programs at the Hanford complex and from consultations with film dosimeter processors and related authoritative groups. Consultations were made on both the technical and administrative aspects of the study with many government and private authorities. Reviews were made of existing programs in other countries, and discussions were held with key personnel at several foreign laboratories of special interest.

Visits were made to four U.S. Atomic Energy Commission sites and six commercial dosimeter film processors to become re-acquainted with the dosimetry practices used in these laboratories and to obtain suggestions on many aspects of the study.

The statistical approaches to this study were discussed with experts during visits to the Food and Drug Administration and to the Applied Mathematics Division of the National Bureau of Standards. Approaches to the preparation of performance criteria in general and their application in industry were discussed with representatives of the Food and Drug Administration. A member of the National Bureau of Standards discussed the study and examined the facilities and equipment used in the experimental program during a visit to Battelle-Northwest.

Also, a visit was made to a major dosimeter film manufacturer to discuss problems associated with dosimeter film manufacture, film manufacturing control limits, and film processing.

The National Sanitation Foundation was visited at Ann Arbor, Michigan to discuss the various methods for establishing performance criteria and to assure integration between this study and their program. The technical representative in charge of the National Sanitation Foundation program also visited Battelle-Northwest to inspect calibration facilities and discuss techniques during the course of the study.

IDENTIFICATION OF FACILITIES FOR A FILM DOSIMETRY CALIBRATION LABORATORY

The extensive experience available relating to the operation of film dosimeter processing facilities was examined to determine the requirements for the building, equipment, staff and cost for the establishment and for the operation of a Film Dosimetry Calibration Laboratory. The information gained during visits to processors' facilities as well as the experience of Battelle-Northwest in operating similar facilities and programs contributed to this aspect of the study.

V. EXPERIMENTAL RESULTS

The experimental program provided a measure of the current performance level of film dosimeter processors and provided the data for deriving the performance criteria. The details of the experimental program and the statistical treatment of the collected data are presented in Appendix B.

The experimental program was designed to collect performance data in a total of nine radiation categories or sub-categories. The selection basis for the radiation categories was previously discussed. Table I summarizes these radiation categories by type of radiation, radiation energy range and radiation dose equivalent range.

Film dosimeter processors estimated the exposure to the test dosimeters and returned their data for analysis. The results were computerized for ease in analysis. The relationship between the dose evaluated, D_i , and the dose delivered, E_i , was taken to be

$$D_i = \alpha + \beta E_i + \epsilon_{E_i} \quad (1)$$

where α and β are systematic bias parameters, and ϵ_{E_i} is a random variable with a mean equal to zero and a variance, $\sigma_{E_i}^2$, dependent on the exposure level E_i . The range of values of α and β for each test irradiation is summarized in Table II. The last two columns of the table give the number of processors detected as having $\alpha \neq 0$ or $\beta \neq 1$; that is, the number of processors with a systematic bias in their process. About 70% of the α 's tested were not equal to zero, and nearly 90% of the β 's tested were not equal to one. Hence, nearly 90% of the processes were detected as having some systematic bias present.

TABLE I. *Radiation Categories*^(a)

<u>Radiation Category</u>	<u>Radiation Energy Range</u>	<u>Dose Equivalent Range, mrem</u>
1. Photon		
A. High Energy	200 keV to 3 MeV	40 to 1000
B. High Dose	200 keV to 3 MeV	20,000 to 800,000
C. Intermediate Energy	50 keV to 200 keV	40 to 1000
D. Low Energy	15 keV to 50 keV	40 to 600
2. Beta	Uranium or ⁹⁰ Sr	40 to 1000
3. Neutrons		
A. Fast	PuBe (4.5 MeV)	200 to 1000
B. Thermal	0.025 eV	40 to 500
4. Mixtures		
A. Photons	200 keV to 3 MeV 15 keV to 50 keV	40 to 1000
B. Photons + Beta	200 keV to 3 MeV Uranium or ⁹⁰ Sr	40 to 1000

(a) *The performance criteria are defined only within the radiation energy range and dose equivalent range indicated in Table I. A quality factor of one was used to relate photon exposures and beta dose measurements to dose equivalent. The fluence to dose equivalent relationships recommended by the National Committee on Radiation Protection and Measurements⁽⁸⁾ were used in Category 3 (Neutrons).*

TABLE II. *Experimental Results--Range of Systematic Bias Parameters*

Radiation Category	Number of Processors	α		β		No. of	
		Range (mrem)		Range		$\alpha = 0$	$\beta = 1$
1. Photon							
A. High Energy	34	-49	57	0.54	1.17	27	33
B. High Dose	33	-19,059	48,476	0	1.48	28	32
C. Intermediate Energy	27	-54	141	0.29	3.20	18	24
D. Low Energy	23	-20	38	0.01	2.46	17	21
2. Beta	31	-93	46	0.56	2.64	19	29
3. Neutrons							
A. Fast	27	-139	552	0.03	2.59	10	20
B. Thermal	16	-61	582	0.16	7.33	9	15
4. Mixtures							
A. Photons							
1) High Energy	17	-77	42	0.73	1.92	16	14
2) Low Energy	13	-138	119	0.15	12.39	9	11
B. Photons + Beta							
1) Photons - High Energy	31	-51	70	0.60	1.32	22	24
2) Beta	31	-87	74	0.20	2.49	23	30

The magnitude of the observed systematic bias for each radiation category for which performance criteria are proposed is shown in Table III. The bias observed is expressed as a percent of the dose. The observed performance of commercial, AEC laboratories, and military installation film dosimeter processors is shown. Many processors in each of the three groups have demonstrated good performance with respect to bias and are tabulated in the 0 to $\pm 10\%$ range. Others have considerably poorer performance placing them in the $\pm 25\%$ to $\pm 100\%$ range, or the greater than $\pm 100\%$ range.

TABLE III. *Experimental Results--Maximum Bias Value in Each Radiation Category*

*Bias - Percent Radiation Category	Number of Processors											
	Commercial				AEC Laboratory				Military			
	0-10	10-25	25-100	>100	0-10	10-25	25-100	>100	0-10	10-25	25-100	>100
1. Photon												
A. High Energy	1	6	3	1	3	5	6	0	2	5	2	0
B. High Dose	2	4	5	0	4	6	4	0	1	0	7	0
C. Intermediate Energy	1	1	6	3	1	4	4	0	1	1	3	2
D. Low Energy	3	3	4	1	1	0	6	0	0	0	5	0
2. Beta	2	2	6	1	4	6	2	0	3	3	2	0
3. Neutrons												
A. Fast	1	1	6	2	1	2	4	3	0	1	5	1
B. Thermal	2	1	1	5	0	1	2	0	0	0	2	2
4. Mixtures												
A. Photons												
1) High Energy	0	3	1	0	4	1	2	0	2	2	2	0
2) Low Energy	0	1	1	1	1	2	3	0	0	0	3	0
B. Photons + Beta												
1) Photon - High Energy	3	5	2	1	7	4	2	0	1	5	1	0
2) Beta	0	4	6	1	0	4	8	0	1	4	3	0

An estimate of the variance was computed from Equation (2):

$$S_i^2 = \sum_{j=1}^{n_i} (D_{ij} - \overline{D}_i)^2 / (n_i - 1) \quad , \quad (2)$$

$$S_i^2 = \text{Sample variance,}$$

$$D_{ij} = \text{Reported exposures at each of} \\ i = 1, \dots, m \text{ dose levels } E_i,$$

$$\overline{D}_i = \text{Average Dose at each dose level,}$$

$$n_i = \text{Number of reported exposures.}$$

A plot of the variance estimates as a function of dose level suggested that an effective criterion for the variance-dose relationship for most radiation categories could be defined as

$$\sigma_i^2 = \kappa E_i \quad (3)$$

where

$$\kappa = \text{a constant to be determined,}$$

$$E_i = \text{delivered dose.}$$

For possible clarification, this criterion can be expressed as the relative error, R_i , at the 95% confidence level by the equation

$$R_i = \frac{2\sigma_i}{E_i} \times 100 = 200 \sqrt{\kappa/E_i} \quad . \quad (4)$$

Once κ is specified, then Equation (4) can be used to express the variance criterion in terms of relative error at any dose level E_i .

The range of estimates of relative error values for each test irradiation is summarized in Table IV. The table shows that at some dose level for each radiation category at least one processor was estimated to have no relative error, except in radiation category-3A, Neutrons-Fast. This was due to the

rounding off processes at the low dose values. The maximum values in the table show relative errors to 600% and beyond. It should be recalled these values are relative errors expressed as a percent of the dose. Any error due to the presence of systematic bias is not included in this value.

TABLE IV. *Experimental Results--Range of Relative Error Estimates: $\frac{\sigma}{E} \times 100$*

<u>Radiation Category</u>	<u>Number of Processors</u>	<u>Relative Error Range, %</u>
1. Photon		
A. High Energy	34	0-59
B. High Dose	33	0-110
C. Intermediate Energy	27	0-620
D. Low Energy	23	0-140
2. Beta	31	0-170
3. Neutrons		
A. Fast	27	1-450
B. Thermal	16	0-3500
4. Mixtures		
A. Photons		
1) High Energy	17	0-94
2) Low Energy	13	0-270
B. Photons + Beta		
1) Photon - High Energy	31	0-280
2) Beta	31	0-65

The test of whether or not a processor meets the variance performance criterion defined by Equation (3) is based on the estimate of S_i^2 . To pass the test, the following must hold:

$$S_i^2 < \frac{\kappa E_i \chi_{\alpha; n_i-1}^2}{n_i - 1}, \quad (5)$$

n_i = number of exposures at dose level E_i ,

$\chi_{\alpha; n_i-1}^2$ = chi-square value at α probability level (selected from a table).

The chi-square test is a standard statistical test of the hypothesis that the variance, σ_i^2 , is less than κE_i . Alpha is a probability level determined by the number of dose levels, i , in the radiation category of interest. For three radiation categories, it was reasonable to relate the variance observed and the dose by the equation

$$\sigma_i^2 = \kappa E_i^2 \quad . \quad (6)$$

The variance performance criterion expressed as the relative error at the 95% confidence level for these three radiation categories or sub-categories is then given by the equation

$$R_i = \frac{2\sigma_i}{E_i} \times 100 = 200 \sqrt{\kappa} \quad . \quad (7)$$

The test of whether or not a processor meets the criterion defined by Equation (6) is again based on the estimate of S_i^2 . To pass the test, the following must hold:

$$S_i^2 < \frac{\kappa E_i^2 \chi_{\alpha; n_i-1}^2}{n_i-1} \quad . \quad (8)$$

All the terms used in Equations (6-8) are the same as defined for Equations (3-5).

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VI. PERFORMANCE CRITERIA

The systematic bias and the "random" variation were chosen as performance features to be used in establishing film dosimeter performance criteria. These performance criteria are to some extent unique in that they require a separation of the bias and variance parameters in the performance analysis.

The action required on the part of a processor to correct for errors due to calibration procedures and methods which give rise to bias is different than the action required to control film processing and evaluation methods which give rise to errors due to variance. The bias aspect of these performance criteria is concerned almost exclusively with the accuracy of the calibration and the evaluation of film dosimeters. Action by processors to minimize or virtually eliminate bias should be relatively straightforward. One needs to identify and correct the source of error in his calibration and evaluation methods. If the bias and variance parameters are not separated, it may be difficult to identify the source of performance difficulties and consequently to make the required changes.

The bias performance criteria were developed to encourage processors to eliminate any bias in excess of 10% (expressed as a percent of dose) or if this is not possible, it will be plausible for a processor to make an over-all bias correction. After excessive bias is eliminated or corrected for, a variance performance criterion needs to be met for a processor to be identified as meeting these film dosimeter performance criteria.

In analyzing any set of data, there is a possibility that a discrepant measurement or outlier will be found and that its use will lead to poor decisions. Film dosimeter measurement data can contain outliers due to many sources: data recording errors, damaged film and incorrect exposures are but a few. Some potential sources of outliers are not within the control

of the processor, and therefore, justify the inclusion of a test to remove outliers from the data prior to the bias and variance analyses. Appendix B presents the procedure for making an outlier test. Only a single datum within a radiation category test may be discarded as an outlier and then only if it clearly is identified as an outlier by the test prescribed. If more than one outlier is detected in a given set of data, then none of the data may be discarded and the analysis should proceed using all of the measurements. This procedure is based on the concept that the simultaneous occurrence of several outliers may be due to a lack of control of the dosimeter evaluation processes and, hence, is a manageable responsibility of the processor.

After tests for outliers have been completed, the estimation of the bias parameters a' and b' is computed from Equations (B-23 and B-24) (Appendix B), respectively. If bias is found, a test is made to see if the bias exceeds 10% of the dose at each dose level by determining if

$$\frac{D(b' - 1) + a'}{D - a'} > 0.1 \quad (9)$$

where

D = Original dose estimate

a' = Weighted least squares estimate of α from Equation (B-23), Appendix B

b' = Weighted least squares estimate of β from Equation (B-24), Appendix B.

If the calculated quantity of Equation (9) does not exceed 0.1, then further bias considerations are not necessary and the bias portion of the performance criteria is met. If a bias greater than 10% is found, then a simple bias correction formula for the current and future measurements is applied.

$$D_c = \frac{D - a'}{b'} \quad (10)$$

where

D_c = Corrected dose estimate

D = Original dose estimate

a' = Weighted least square estimate of α from Equation (B-23)

b' = Weighted least square estimate of β from Equation (B-24).

By applying this bias correction, the bias portion of the performance specification is met. The correction may be applied directly to the film dosimeter calibration data by the processor to avoid repeated corrections to each dose evaluation made.

Figure 1 illustrates the application of this bias correction to one of the poorer sets of data from the test irradiation program.

If a process has a bias estimate, $b' < 1$, then use of the correction formula would increase the variance. Conversely, if $b' > 1$, then the bias correction would decrease the variance. In all cases of performance evaluation, the data should be corrected for excessive bias, if it exists, prior to applying the variance specification test. For processes with good variance performance, bias corrections should not present a difficulty in meeting the performance specifications. However, if the bias factor b' , is less than one and the variance performance of the processor is marginal then the bias corrections may result in failure of the variance portion of the performance criteria. If this should occur, it is an indication that the processor involved needs to make some performance improvements.

The bias performance of the five processors selected for derivation of the variance performance criteria was examined, not as a basis for establishing a bias performance criterion, but rather in the interest of determining if these five processors had significant bias in their operations. Their bias performance was scattered throughout the bias range including three values exceeding 100%. Appropriate action to eliminate or minimize the observed bias is necessary for these processors.

FIGURE 1. *Uncorrected and Corrected Sample Data for Process with Lowest "b" for the Photon-Intermediate Energy Radiation Category*

To establish a variance performance criteria, the change in relative variation, standard deviation/dose, was examined for all radiation categories of the test irradiation program. With the exception of the 1-B (photon-high dose), 3-A (neutron fast) and X-ray component of the 4-A (mixtures) radiation

categories, the relative variations were found to decrease with increasing dose. The observed relative variations for the exceptions named were approximately constant. These two types of observations can be expressed as

$$\sigma_E^2 = \kappa E_i \quad (\text{for decreasing relative variations}), \quad (11)$$

$$\sigma_E^2 = \kappa E_i^2 \quad (\text{for constant relative variations}) \quad (12)$$

where σ_E^2 is the variance at dose level, E_i , and κ is a proportionality constant.

The decision to use the $\sigma_E^2 = \kappa E_i^2$ relation for the 1-B (photon-high dose) and the X-ray component of the 4-A (mixtures) radiation categories was made to assure adequate performance in these radiation categories commensurate with the level of performance observed in the test irradiation data.

From a purely procedural point of view, this same relation should have also been used for radiation category 3-A (neutron-fast); however, the $\sigma_E^2 = \kappa E_i$ relationship was used to provide a less demanding, yet reasonable performance criteria for this category. Data analysis to establish a value of " κ " for the fast neutrons when Equation (11) was used as the variance specification yielded a κ value of 8. When the relative error corresponding to this κ value was calculated, it ranged from 40% at 200 mrem to only 20% at 1000 mrem. Judgment indicated these values were overly restrictive for the current capabilities of the nuclear track emulsions used in personnel neutron dosimetry. The data analysis, to establish a value of κ when Equation (12) was used, yielded a κ value of 0.03, which corresponds to a constant relative error of 35% over the dose equivalent range from 200 to 1000 mrem. This value was also judged to be too restrictive for the current state of the technology of personnel neutron dosimetry. To provide a

reasonable specification for initial use in performance evaluation, the use of Equation (11) and a κ value of 40 were selected. This provides an increasing variance limit with decreasing dose equivalent and requires reasonably attainable levels of performance.

In the establishment of the performance criteria, the technical methods of the study were carried through to completion without a professional judgment relating to the significance of or the need for the levels of performance derived. Once the derivations were completed, the criteria values obtained were examined to determine their reasonableness. In several radiation categories, the methods of data analysis yielded variance performance criteria that would have required relative error control to less than 10%. This was judged to be more restrictive than necessary. Consequently, the variance performance criteria were adjusted so that variance performance to less than 10%, expressed as relative error, would not be required.

These performance criteria are based on the level of performance observed early in 1967. They should be regarded as being reflective of the performance capabilities at that time and should be reviewed for modification as appropriate to meet changing conditions of film dosimeter technology. They may also merit review and change based on the practical experience gained through their adoption and routine application. They have not been based on a fundamental, unvariable need for a certain performance level. Basing criteria on a fundamental need leads to many unresolved problems relating to radiation dose effects of a biological nature and is clearly a major study in itself and beyond the scope of this current study.

The variance performance criteria for all radiation categories except 1-B (photon-high dose) and the X-ray component of the 4-A (mixtures) category is to require that

$$S_i^2 < \frac{\kappa E_i^2 \chi_{\alpha_i; n_i-1}^2}{n_i - 1} \quad (13)$$

For the l-B (photon-high dose) and the X-ray component of 4-A (mixtures) categories, the variance performance criteria require that

$$S_i^2 < \frac{\kappa E_i^2 \chi_{\alpha_i; n_i-1}^2}{n_i - 1} \quad (14)$$

where

S_i^2 = Sample variance

κ = Performance constant

E_i = Dose level

n_i = Number of exposures

$\chi_{\alpha_i; n_i-1}^2$ = Tabled chi-square value at α_i probability and n_i-1 measurements.

Appendix B discusses the calculation of the values of κ which determine the values of the variance performance criteria. For the performance criteria recommended for adoption by this study, the κ values listed in Table V are appropriate. For some radiation categories, two κ values are presented. This arises from the feature of limiting the relative error to a value not less than 10% over the entire dose range of each radiation category.

To visualize the magnitude of the variance performance criteria, the relative error corresponding to the variance performance criteria can be calculated. The relative error at the 95% confidence level for variance specification, $\sigma^2 = \kappa E$, is given by the equation:

$$R_i = \frac{2\sigma_i}{E_i} \times 100, \quad (15)$$

or substituting for σ_i ,

$$R_i = 200 \sqrt{\frac{\kappa}{E_i}}. \quad (16)$$

For variance specification, $\sigma^2 = \kappa E^2$, the relative error at the 95% confidence level is given by

$$R_i = 200 \sqrt{\kappa}. \quad (17)$$

TABLE V. *Variance Performance Criteria*

<u>Radiation Category</u>	<u>κ Values</u>			
	$\sigma^2 = \kappa E$		$\sigma^2 = \kappa E^2$	
	<u>Dose Range-1,</u> <u>mrem</u>	<u>κ</u>	<u>Dose Range-2,</u> <u>mrem</u>	<u>κ</u>
1. Photon				
A. High Energy	40-1000	2.3		
B. High Dose			20,000-8,000,000	0.0025
C. Intermediate Energy	40-1000	8.5		
D. Low Energy	40-240	0.6	240-600	0.0025
2. Beta	40-480	1.2	480-1000	0.0025
3. Neutrons				
A. Fast	200-1000	40		
B. Thermal	40-380	0.9	380-500	0.0025
4. Mixtures				
A. Photons				
1) High Energy	40-1000	2.3		
2) Low Energy			40-600	0.005
Total	40-600	2.9		
B. Photons + Beta				
1) Photon-High Energy	40-1000	2.3		
2) Beta	40-1000	3.3		

Table VI presents the variance performance criteria for some selected dose levels in terms of relative error calculated from the appropriate Equation (16) or (17). These values are presented graphically in Figures 2 through 12.

The performance level for any dose in terms of relative error for dose Range-1 of Table V can be calculated from Equation (16). The performance level for any dose in terms of relative error for dose Range-2 of Table V can be calculated from Equation (17).

The variance performance criteria were designed to assure a high probability of passing the tests for each processor whose performance meets the variance specification. An important factor considered in the establishment of these performance criteria was the fluctuations that will occur in measured performance solely due to the statistical variations of the measurements. For example, to establish a variance performance criterion, expressed as relative error, at say 40% and to test rigidly against that value to determine compliance, actually requires performance considerably better than the 40% to assure compliance on every test. A processor meeting the 40% criterion with 95% confidence will fail 5% of the time on a statistical basis alone. If there are several test points all or nearly all of which the processor must meet, his ability to pass is rapidly decreased due solely to the design of the performance measurement system. The performance criteria advanced by this study have avoided this difficulty by designing performance criteria tests that take into account the statistical nature of the evaluation procedures. The χ^2 function used in the variance performance Equations (13) and (14) allows for the statistical variations that are normally to be expected in evaluation of the performance of processors. This test method provides maximum flexibility in designing the performance evaluation program and provides for the use of various numbers

of dosimeters at a various number of dose levels while still maintaining a constant required level of performance.

In summary, a set of variance performance criteria are presented. These are defined rigidly by the κ values given in Table V and Equations (13) and (14) and correspond to the relative error values given in Table VI. The test procedure to compare actual performance against these performance criteria considers and makes appropriate allowances for:

- The confidence level, within which an adequate processor can meet these criteria on any given test
- The use of a various number of dosimeters at each dose level
- The use of a various number of dose levels within each radiation category
- The provision of an equally rigid performance evaluation for any combination of the above three factors.

It is important to emphasize that calculating the estimate of the relative error for a set of data and finding it to fall within the values tabulated in Table VI is not a test to determine if the variance performance criteria are met. One first needs to test for bias, eliminate or correct for bias if necessary, and then test the variance performance in Equations (13) and (14) to determine if the variance performance criteria are met.

Figures 2 through 12 show graphically the relationship between the performance criteria (based on variance alone) expressed as relative error and the dose equivalent for each radiation category. For comparative purposes, the performance levels recommended by the National Sanitation Foundation (NSF) are shown on the graphs for radiation categories similar to those used in the NSF study. It should be remembered that the NSF criteria are a combination of bias and variance factors. In the study reported here the bias factors were not included in the variance performance, but were treated with a separate performance criterion.

TABLE VI. *Variance Performance Criteria for Selected Dose Levels Expressed as Relative Error*

<u>Radiation Category</u>	<u>Dose Level, mrem</u>	<u>Relative Error</u>
1. Photon		
A. High Energy	40	48
	60	39
	100	30
	250	19
	500	14
	750	11
	1,000	10
B. High Dose	20,000	10
	400,000	10
	800,000	10
C. Intermediate Energy	40	92
	60	75
	100	58
	250	37
	500	26
	750	21
	1,000	18
D. Low Energy	40	24
	60	20
	100	15
	240	10
	300	10
	450	10
	600	10
2. Beta	40	35
	60	28
	100	22
	250	14
	480	10
	600	10
	800	10
	1,000	10
3. Neutrons		
A. Fast	200	89
	400	63
	600	52
	800	45
	1,000	40

TABLE VI. (contd)

<u>Radiation Category</u>	<u>Dose Level, mrem</u>	<u>Relative Error</u>
B. Thermal	40	30
	60	24
	100	19
	250	12
	300	11
	380	10
	400	10
	500	10
4. Mixtures		
A. Photons		
	1) High Energy	
	40	48
	60	39
	100	30
	250	19
	500	14
	750	11
	1,000	10
	2) Low Energy	
	40	14
	60	14
	100	14
	250	14
	400	14
	600	14
	3) Total	
	40	54
	60	44
	100	34
	250	22
	400	17
	600	14
B. Photons + Beta		
	1) Photon-High Energy	
	40	48
	60	39
	100	30
	250	19
	500	14
	750	11
	1,000	10
	2) Beta	
	40	57
	60	47
	100	36
	250	23
	500	16
	750	13
	1,000	11

FIGURE 2. Radiation Category 1-A, Photon, High Energy

FIGURE 3. Radiation Category 1-B, Photon, High Dose

FIGURE 4. Radiation Category 1-C, Photons, Intermediate Energy

FIGURE 5. Radiation Catagory 1-D, Photon, Low Energy

FIGURE 6. Radiation Catagory 2, Beta

FIGURE 7. Radiation Category 3-A, Neutrons, Fast

FIGURE 8. Radiation Category 3-B, Neutrons, Thermal

FIGURE 9. Radiation Category 4-A, Mixtures, Photons-Gamma Ray Component

FIGURE 10. Radiation Category 4-A, Mixtures, Photons-X-ray Component

FIGURE 11. Radiation Category 4-B, Mixtures, Photons, Beta-Photon Component

FIGURE 12. Radiation Category 4-B, Mixtures, Photons, Beta-Beta Component

There is a probability, of course, that on any single test an adequate processor will fail to meet the criteria and, conversely, that an inadequate processor will meet the criteria. The power of the variance performance criteria may be noted by considering an example. Assume that a test in Radiation Category 1-A, Photon-High Energy is conducted and that the process being tested is unbiased and normally distributed with variance $\sigma^2 = \kappa'E$. If $\kappa' = 2.3$, then the process barely meets the variance criteria. If $\kappa' \neq 2.3$, then the process does or does not meet the criteria, depending on whether $\kappa' < 2.3$ or $\kappa' > 2.3$. The probabilities of such a process passing the variance test for five values of κ' and four test procedures are given in Table VII.

TABLE VII. Probability of Passing the Variance Tests Under Various Conditions

κ'	Exposure Level	Relative Error $\frac{2\sigma}{E}(100)\%$	P			
			$n_i = 5$ $m = 4$	$n_i = 4$ $m = 5$	$n_i = 6$ $m = 5$	$n_i = 5$ $m = 6$
1	60	26				
	120	18				
	240	13	0.999	0.999	0.999	0.999
	500	9				
	1,000	7				
2	60	36				
	120	26				
	240	19	0.921	0.913	0.924	0.923
	500	13				
	1,000	9				
2.3	60	39				
	120	28				
	240	20	0.850	0.850	0.850	0.850
	500	14				
	1,000	10				
3	60	45				
	120	32				
	240	23	0.650	0.658	0.604	0.614
	500	16				
	1,000	11				
4	60	51				
	120	37				
	240	26	0.340	0.396	0.292	0.308
	500	18				
	1,000	13				

Again, the relative error column is given in order to assist in the interpretation of the κ 's. The numbers in the four columns under P are the probabilities of passing variance tests with n_i measurements at each of m exposure levels.

The variance tests, under the hypothesized conditions, yield the same probabilities regardless of the exposure levels used. When $\kappa' = 2.3$, the variance criterion, the probability of passing the test is always 0.85. That is, when a process just meets the criterion, the probability of passing is independent of how the data is collected for the test. If $\kappa' = 1$, the process has only a slight chance of failing one of these tests: $P = 0.999$ for all four tests. If $\kappa' = 4$, the process will pass the test 30 to 40 times out of 100 depending on which test procedure is applied: P ranges from 0.292 to 0.396.

For each test procedure, the probability of passing decreases with increasing κ' , as should be expected. Comparing the probabilities for the first two test procedures (20 data) with those for the last two test procedures (30 data), shows that the more data the better the test in the sense that those processes meeting the criterion have a higher probability of passing the test and those not meeting the criterion a lower probability of passing. On the same basis, comparing the first test procedure with the second and the third with the fourth indicates that more exposures at less levels is the preferable allocation when considering a fixed total number of exposures. This last property suggests that the Laboratory should restrict itself to a single test procedure (except for choice of exposure levels) for all processors during any one test period. If the Laboratory allows the number of exposures and exposure levels to vary from processor to processor, it then allows different probabilities of passing the test for two identical processes.

VII. COMPARISONS OF EXPERIMENTALLY OBSERVED PERFORMANCE AND THE PROPOSED PERFORMANCE CRITERIA

The performance of all processors participating in the test irradiation program was analyzed to determine how well current performance met the proposed criteria. Although the bias performance is not scored as "passed" or "failed" due to the use of a bias correction factor when bias is in excess of 10% (expressed as a percent of dose), it is of interest to examine how many processors would have been required to make a bias correction based on their performance in this experimental program. The number of processors having bias values in several bias ranges was presented in Section V (Table III). This table is repeated here as Table VIII for reference.

In some subcategories, all processors were found to have biases greater than 10% and, hence, would have been required to make a bias correction. Averaged over all radiation categories, the percentage of dose evaluations requiring a bias correction is given in Table IX. This table indicates that about 85% of all measurements reported had bias in excess of 10% and required some bias correction or bias elimination effort on the part of the processor to meet the proposed bias performance criteria. Three to 16% of the measurement had bias present in excess of 100%.

The performance observed in the test irradiation program is compared to the proposed variance performance criteria in Tables X and XI. Table X shows the number of processors of all types that would have passed or failed the variance portions of the performance criteria. All test data used in constructing the variance performance tables were corrected for bias prior to variance analysis. Averaged over all radiation categories, about 75% of the tests were passed. Table X also gives the variance performance criteria test results for each type of processor. Averaged over all

TABLE VIII. *Experimental Results--Maximum Bias Value in Each Radiation Category*

*Bias - Percent Radiation Category	Number of Processors											
	Commercial				AEC Laboratory				Military			
	0-10	10-25	25-100	>100	0-10	10-25	25-100	>100	0-10	10-25	25-100	>100
1. Photon												
A. High Energy	1	6	3	1	3	5	6	0	2	5	2	0
B. High Dose	2	4	5	0	4	6	4	0	1	0	7	0
C. Intermediate Energy	1	1	6	3	1	4	4	0	1	1	3	2
D. Low Energy	3	3	4	1	1	0	6	0	0	0	5	0
2. Beta	2	2	6	1	4	6	2	0	3	3	2	0
3. Neutrons												
A. Fast	1	1	6	2	1	2	4	3	0	1	5	1
B. Thermal	2	1	1	5	0	1	2	0	0	0	2	2
4. Mixtures												
A. Photons												
1) High Energy	0	3	1	0	4	1	2	0	2	2	2	0
2) Low Energy	0	1	1	1	1	2	3	0	0	0	3	0
B. Photons + Beta												
1) Photon - High Energy	3	5	2	1	7	4	2	0	1	5	1	0
2) Beta	0	4	6	1	0	4	8	0	1	4	3	0

radiation categories, about 60% of the tests were passed by the commercial processors, about 90% by the AEC contractor processors, and about 80% by the military processors.

TABLE IX. *Experimental Results--Observed Processor Bias Performance*

<u>Type of Processor</u>	<u>Percent of Measurements Within Indicated Bias Ranges Averaged Over All Radiation Categories</u>			
	<u><10%</u>	<u><25%</u>	<u><100%</u>	<u>>100%</u>
Commercial	15	45	84	16
AEC Laboratory	24	56	97	3
Military	15	44	93	7

A relatively few processors contributed a high percentage of the failures noted. A detailed analysis of the failures shows that 3 (27%) of the commercial processors gave rise to 50% of the failures listed for their group, 3 (20%) of the AEC Laboratory processors gave rise to 58% of the failures listed for their group and 3 (33%) of the military processors gave rise to 60% of the failures for their group.

Table XI, in addition to repeating the data in Table X, shows the changes that would result if all the processors listed as failing in Table XI made a 10% or 50% improvement in their performance, i.e., relative error plus 0.1 (relative error) and relative error plus 0.5 (relative error).

Table XII shows the changes in passing and failing performance at 0, 10 and 50% improvement by all processors. The values listed in the Table are averaged over all radiation categories.

A 10% improvement in performance nets a 4, 1, and 2% improvement in meeting the proposed performance criteria by commercial, AEC laboratory and military processors, respectively. A 50% improvement in performance nets a 19, 7 and 12% improvement in meeting the proposed performance criteria by commercial, AEC laboratory and military processors, respectively.

TABLE X. *Observed Variance Performance Compared to Proposed Performance Criteria
(Corrected for Bias)*

<u>Radiation Category</u>	<u>Total No. of Processors</u>		<u>No. of Commercial Processors</u>		<u>No. of AEC Processors</u>		<u>No. of Military Processors</u>	
	Pass	Fail	Pass	Fail	Pass	Fail	Pass	Fail
1. Photon								
A. High Energy	29	5	8	3	13	1	8	1
B. High Dose	23	10	5	6	12	2	6	2
C. Intermediate Energy	21	6	8	3	8	1	5	2
D. Low Energy	15	7	6	5	5	1	4	1
2. Beta	24	7	7	4	9	3	8	0
3. Neutrons								
A. Fast	20	7	7	3	9	3	8	0
B. Thermal	5	11	3	6	2	1	0	4
4. Mixtures								
A. Photons								
1) High Energy	12	1	4	0	5	1	3	0
2) Low Energy	10	3	1	3	6	0	3	0
B. Photons + Beta								
1) Photon - High Energy	28	3	8	3	12	0	8	0
2) Beta	25	6	7	4	11	1	7	1

TABLE XI. Status of Variance Performance with 0%, 10% and 50% Improvements

Radiation Category		Number of Processors																	
		Commercial						AEC						Military					
		% Improvement						% Improvement						% Improvement					
		0		10%		50%		0		10%		50%		0		10%		50%	
P(a)	F(b)	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F
1. Photon																			
A.	High Energy	8	3	9	2	11	0	13	1	13	1	14	0	8	1	8	1	9	0
B.	High Dose	5	6	5	6	9	2	12	2	12	2	13	1	6	2	6	2	7	1
C.	Intermediate Energy	8	3	8	3	10	1	8	1	8	1	8	1	5	2	5	2	5	2
D.	Low Energy	6	5	7	4	9	2	5	1	5	1	6	0	4	1	4	1	5	0
2. Beta		7	4	7	4	9	2	9	3	10	2	11	1	8	0	8	0	8	0
3. Neutrons																			
A.	Fast	7	3	7	3	8	2	9	1	9	1	10	0	4	3	5	2	6	1
B.	Thermal	3	6	3	6	3	6	2	1	2	1	2	1	0	4	0	4	2	2
4. Mixtures																			
A.	Photons																		
	1) High Energy	4	0	4	0	4	0	5	1	5	1	5	1	3	0	3	0	3	0
	2) Low Energy	1	3	2	2	2	2	6	0	6	0	6	0	3	0	3	0	3	0
B.	Photons + Beat																		
	1) Photon - High Energy	8	3	9	2	9	2	12	0	12	0	12	0	8	0	8	0	8	0
	2) Beta	7	4	8	3	10	1	11	1	11	1	12	0	7	1	7	1	8	0

(a) Passes proposed variance performance criteria

(b) Fails to meet proposed variance performance criteria

Based on this single irradiation test, the commercial processors met about 60% of the proposed variance performance criteria. This does not translate directly to the conclusion that 40% of the criteria would not be met. In some instances, processors participated in radiation categories where they are not likely to seek evaluation and do not offer commercial service. Additionally, once processors have a set of performance criteria that define adequate performance and provide a mechanism to evaluate their performance, appropriate improvements are likely to be made. Even small changes in processing or evaluation methods can yield large improvements in performance.

TABLE XII. *Processor Variance Performance -
Percent of Categories Passed*

<u>Type of Processor</u>	<u>Observed Performance</u>	<u>Performance After Improvement</u>	
	<u>0% Improvement</u>	<u>10% Improvement</u>	<u>50% Improvement</u>
Commercial	62	66	81
AEC Laboratory	88	89	95
Military	80	82	92

Processors who have not fully exploited the film dosimetry technology may be expected to make necessary changes and attain necessary improvements in performance when they recognize their deficiencies and have a set of performance criteria with which to assess their current performance level.

VIII. NEED FOR A FILM DOSIMETER EVALUATION PROGRAM

The experimental program conducted as a part of this study provided the data not only to derive the proposed performance criteria, but also to evaluate the current performance level of each processor relative to the developed performance criteria. The evaluation of the performance of individual film processors form the basis to determine whether a Film Dosimeter Evaluation Program is necessary and needed at the present time.

The study has divided performance into two variables, bias and variance. First, consider the bias that was found to exist among film dosimeter processors. Was the bias observed of sufficient magnitude to require the specification of a bias performance criterion? Bias is a measure of the difference between the average dose evaluated when a number of film dosimeters are exposed to a given dose and the "true" value of the given dose. The bias factor is an important consideration in assessing and in controlling the performance of film dosimeter processors. If each processor had well calibrated radiation sources and ideal calibration geometrics and dose evaluation methods, then no biases should exist.

This study demonstrated that significant biases do exist among film dosimeter processors. The range of bias values observed and the frequency of occurrence within selected bias ranges are repeated here in Table XIII. Biases ranged to several hundred percent. A bias factor of 100% means the dose evaluation may be in error by 100% and also any dose summation of many dosimeter evaluations may be in error by 100%.

Bias is an error that can be controlled or corrected for with relative ease. Biases that exceed a few tens of percent should be reduced or eliminated. Clearly, bias values exceeding 100% are not justifiable. Biases which result in dose evaluation errors of this magnitude bargain strongly for the

TABLE XIII. *Experimental Results--Maximum Bias Value in Each Radiation Category*

*Bias - Percent Radiation Category	Number of Processors											
	Commercial				AEC Laboratory				Military			
	0-10	10-25	25-100	>100	0-10	10-25	25-100	>100	0-10	10-25	25-100	>100
1. Photon												
A. High Energy	1	6	3	1	3	5	6	0	2	5	2	0
B. High Dose	2	4	5	0	4	6	4	0	1	0	7	0
C. Intermediate Energy	1	1	6	3	1	4	4	0	1	1	3	2
D. Low Energy	3	3	4	1	1	0	6	0	0	0	5	0
2. Beta	2	2	6	1	4	6	2	0	3	3	2	0
3. Neutrons												
A. Fast	1	1	6	2	1	2	4	3	0	1	5	1
B. Thermal	2	1	1	5	0	1	2	0	0	0	2	2
4. Mixtures												
A. Photons												
1) High Energy	0	3	1	0	4	1	2	0	2	2	2	0
2) Low Energy	0	1	1	1	1	2	3	0	0	0	3	0
B. Photons + Beta												
1) Photon - High Energy	3	5	2	1	7	4	2	0	1	5	1	0
2) Beta	0	4	6	1	0	4	8	0	1	4	3	0

need for improved performance with respect to bias and for an evaluation program to assure that bias factors are adequately controlled.

Bias could be virtually eliminated by the establishment of a central film dosimeter calibration facility. By providing calibration exposures to film dosimeters at a central calibration facility, each processor would be assured that his calibration film received the same radiation exposure as that received by every other processor. A top quality central calibration facility would be the key to bias elimination. The central calibration facility would provide a mechanism to avoid the very high bias values found for some processors and would essentially assure the elimination of bias as a significant factor in film dosimeter evaluations.

Second, consider the variance that was found to exist among film dosimeter processors. Was the variance observed of sufficient magnitude to require formulation of a variance specification? Variance is a measure of the variation in dose measurement when a number of dosimeters are exposed at the same dose level. It is an important consideration in assessing how well a processor controls his processing and evaluation methods. In discussing variance, it is convenient to convert the variance to relative error values to more easily visualize its significance. The relative error is defined as

$$R = \frac{2\sigma}{E} \times 100$$

where

R = Relative error,

σ = Square root of the sample variance,

E = Dose at which the variance is measured.

The relative error is the percentage error that may occur at the 95% confidence interval due to the variance, σ^2 , observed at dose level E.

This study demonstrated that significant variances, and consequently significant relative errors, do exist among film dosimeter processors. The range of the relative errors observed are repeated here in Table XIV. Relative errors to several hundred percent were observed. These are judged to be excessive. The observed performance of many processors with investments in facilities and equipment not exceeding that of typical processors demonstrated that adequate variance performance can be reasonably attained.

If film dosimeters are used as part of a radiation protection program, it would seem desirable to control bias and variance more precisely than seems to be currently achieved. A film dosimetry evaluation program would be necessary to determine that the derived performance criteria are met.

Two considerations suggest the need to have in operation a system to assure adequate performance in personnel dosimetry. First, there may be an intrinsic need to demonstrate that the performance of film dosimeter processors is adequate. Second, there may be sufficient indication that reasonable action would result in improvements.

Earlier in this report, the judgment was stated that some system is necessary if one wishes to provide some degree of assurance that film dosimeter processing companies and other groups providing this service are performing in conformance with some minimum performance criteria. It is difficult for those responsible for health and safety to fully discharge their responsibilities without reasonable assurance that personnel film dosimetry is being performed in a consistent, responsible and adequate manner.

The methods of implementation of a Film Dosimeter Evaluation Program are dependent on the degree of regulation which is desired or needed. Broad matters of policy have heavy influence, therefore, on alternate methods of implementation which achieve substantially different degrees of regulatory control.

TABLE XIV. *Experimental Results--Range of Relative Error: $\frac{2\sigma}{E} \times 100$*

<u>Radiation Category</u>	<u>Number of Processors</u>	<u>Relative Error Range, %</u>
1. Photon		
A. High Energy	34	0-59
B. High Dose	33	0-110
C. Intermediate Energy	27	0-620
D. Low Energy	23	0-140
2. Beta	31	0-170
3. Neutrons		
A. Fast	27	1-450
B. Thermal	16	0-3500
4. Mixtures		
A. Photons		
1) High Energy	17	0-94
2) Low Energy	13	0-270
B. Photons + Beta		
1) Photon - High Energy	31	0-280
2) Beta	31	0-65

The procedural methods described in Appendix B and C for assessing the adequacy of performance of a film processor are technically sound and appear to be administratively feasible. The principal areas of option that would accommodate the range of interests of regulatory agencies and other groups should be in the degree to which this system for assessing adequacy is compulsory or voluntary, rather than to attempt to vary the frequency or the intensity of the testing procedures.

Two alternates merit consideration: full regulatory implementation and voluntary implementation.

Full Regulatory Implementation

Under this alternative film dosimeter processors providing service to users of ionizing radiation would be required through the responsible regulatory agency to

participate in the Film Dosimeter Evaluation Program conducted by a Film Dosimetry Calibration Laboratory as described in Appendix C. To continue to provide such services these processing firms or groups would have to meet the performance criteria then in effect and maintain their adequate performance according to the testing schedule in Appendix C.

The responsible regulatory agency would be made aware of the performance of all of those participating in the Evaluation Program. Anyone could request and receive from the Film Dosimetry Calibration Laboratory a current list of firms providing service in conformance with the criteria. Individual firms presumably would want to advertise the fact that they are providing service of a quality which meets the criteria.

This alternate would provide "full" assurance that film dosimetry services are being provided on a sustained basis in conformance with established performance criteria. Means would be readily available to exclude unapproved film processing firms or groups from providing service.

Voluntary Implementation

The alternate arrangement to the full regulatory method of implementation of the Film Dosimeter Evaluation Program consists of the provision for entirely voluntary participation by dosimeter processors. In this method of implementation, the processor desiring to demonstrate his conformance with the proposed criteria would indicate to the Film Dosimetry Calibration Laboratory that he wanted to participate in the Program. The identical test irradiation, data analysis and approval steps would be taken as in the compulsory program. The

Film Dosimetry Calibration Laboratory would, upon request, identify those processors who, by their participation are providing service that meets the performance criteria. The Film Dosimetry Calibration Laboratory would be silent on the point of whether or not other processors have or are participating in the Film Dosimeter Evaluation Program. Processors participating in the Evaluation Program and meeting the performance criteria presumably would want to state this fact in the marketing of their services.

The important feature of this alternate is that no compulsory regulatory program is involved. The extent of voluntary participation by industry is believed to be unpredictable at this time. Users of ionizing radiation could be expected to subscribe to film processors who could demonstrate that their services meet established performance criteria.

There is some value in postulating the situation that would have prevailed if the analyses of the experimental part of this study had indicated that no improvement in the performance of film processors was needed or that improvement was not feasible. Given this hypothetical situation, a likely course of action could have been to make a nominal review of the dosimeter film processors again after two or three years to reassure that adequate performance levels were being maintained.

The next logical question is, if any form of a national Evaluation Program were determined to be undesirable (for whatever reason), what steps could be taken which would provide the possibility of improving the performance of film processors to a point where over all performance would be adequate or substantially improved and reflect the current capability of technology? The most promising answer to this question is to make readily available to film processors, at low cost or no cost, a film dosimeter calibration service which would routinely provide irradiation services for types, energies and magnitudes of radiation exposures embraced by the proposed performance criteria. Although no assurance of adequate performance is inherent in providing this service, reduction and virtual elimination of bias would likely result. Some improvement in variance control would also likely ensue from the very fact that low cost central film dosimeter calibration service would be easily accessible and used. One could anticipate that processors would, consequently desire to upgrade other aspects of film processing.

APPENDIX A
U.S. ATOMIC ENERGY COMMISSION,
NOTICE REGARDING NEED FOR ESTABLISHMENT
OF FILM DOSIMETRY CALIBRATION LABORATORY

APPENDIX A

U.S. ATOMIC ENERGY COMMISSION.*
NOTICE REGARDING NEED FOR ESTABLISHMENT
OF FILM DOSIMETRY CALIBRATION LABORATORY

The Atomic Energy Commission and other users of sources of ionizing radiation presently place considerable reliance on personnel monitoring services, including film dosimetry services, as important factors in the control of exposure to radiation. Various studies have been made by the Commission, the National Bureau of Standards, and others, to evaluate overall performance of the film dosimetry services. While such studies have not yet been sufficiently numerous or broad in scope to reach firm conclusions in view of the very limited suitability of the data for a comparison of their findings, the studies indicate that the accuracy of some dosimetry services may vary.

The Atomic Energy Commission is considering the desirability of issuing for public comment a proposed regulation that would require AEC licensees subject to the personnel monitoring requirements of the Commission's regulations to utilize film dosimetry services which meet certain minimum performance criteria. This requirement would apply both to licensees who operate their own film dosimetry services and to licensees who contract for such services.

In addition, a set of minimum performance criteria is now under consideration to provide standards of accuracy for evaluating film dosimetry services utilized by licensees. These criteria are given in Table I (Table A-1 in this report). They are designed to be applicable for many conditions of radiation exposure and for various film dosimetry monitoring systems. The criteria do not imply that one particular film

* U.S. Atomic Energy Commission, "Notice Regarding Need for Establishment of Film Dosimetry Calibration Laboratory," Federal Register 63, p. 9411. September, 1963.

dosimetry system is superior to another, but are designed to provide a standard for measuring the continuing accuracy of each service. It is expected that such criteria would be revised periodically when the need is demonstrated.

To implement the criteria under consideration, the establishment of a calibration laboratory appears to be desirable. It is hoped that the laboratory will be privately financed. Should this prove impractical, the laboratory might have to be established by the AEC or other agency of the Federal Government.

The Commission is studying the possibility of utilization of such a laboratory for Commission contract activities.

The Commission anticipates that the following factors or premises will be of significance in connection with the possible establishment and operation of the calibration laboratory.

1. The laboratory must have the requisite staff, equipment and procedures to perform the calibration services. An existing laboratory or other establishment having the requisite capability will be considered, as will a proposed new establishment.
2. To assure objectivity, it would appear inadvisable for the laboratory to be established by any group operating a film dosimetry service or manufacturing dosimetry components, including film.
3. Dosimetry services under evaluation will periodically send representative samples of their film badge dosimeters to the calibration laboratory. The dosimeters will be exposed by the calibration laboratory to known quantities of radiation of varying types and returned to the dosimetry services for processing and analysis. The results of the analysis will be transmitted to the calibration laboratory where they will be compared with the calibration laboratory

test exposure information in accordance with applicable statistical techniques. All film dosimetry services will be re-evaluated periodically on a schedule based on their previous performances.

4. The film dosimetry performance criteria listed in Table I are divided into classes (assigned by type of radiation) and sub-classes (assigned by energy ranges). Film dosimetry services require differing degrees of evaluation, according to the coverage provided. (For example, a service providing monitoring for the users of sealed gamma radiography sources generally will not require the extensive review given a service providing monitoring for a large-scale isotopes laboratory operation, where a variety of types of radiation is encountered.)
5. The film dosimetry service will be evaluated in one class or combination of classes and will be evaluated for all energy ranges in each class specified, unless otherwise requested by the service.
6. The calibration laboratory will be expected to demonstrate periodically its ability to perform calibration work accurately so that the Commission can determine that evaluations performed by the laboratory satisfy the Commission's requirements.
7. The laboratory will not be necessarily restricted to the handling of film badges but might in the future include calibration of other similar radiation measuring devices.

Notice is hereby given that the Atomic Energy Commission desires to determine the interest of organizations and other persons in establishing and operating such a laboratory, and is also interested in receiving suggestions and comments, particularly from AEC licensees and contractors, concerning the proposed calibration laboratory and film dosimetry performance criteria. This notice should not be deemed to be an

offer or a request for proposals with respect to the establishment or operation of a calibration laboratory. Persons, organizations, or groups of organizations which are interested in establishing a calibration laboratory, and others, should direct their comments in this matter to the Director, Division of Licensing and Regulation, U.S. Atomic Energy Commission, Washington 25, D.C., within 90 days from date of publication of this notice.

It is suggested that comments filed pursuant to this notice discuss among other things the following questions, taking into account the governing factors and premises previously discussed:

1. Would you be interested in establishing a calibration laboratory without Government financial assistance? If so, how would the laboratory establishment and operation be financed?
2. What additional information from the Commission do you need to aid you in determining the cost of establishing and operating a calibration laboratory?
3. What other information from the Commission do you need to aid you in determining whether or not you are interested in establishing such a laboratory?
4. What suggestions do you have with respect to any of the following?
 - a. What should be the content of the calibration laboratory's findings? In what manner should these findings be released? By publication, by issuance of certificates, or by issuance of reports.
 - b. What distribution should be made of the findings?
 - c. What procedures, equipment and staff do you consider adequate for such a laboratory?

5. What comments do you have with respect to the reasonableness of the performance criteria? Do you suggest any modifications to Table I? (Table A-I in this Report)

Dated at Germantown, Maryland this 23rd day of July, 1963.

FOR THE ATOMIC ENERGY COMMISSION

Signed by

Woodford B. McCool
Secretary

TABLE A-I. Interim Film Dosimetry Performance Criteria

Class	Type of Radiation	Subclass	Energy Range	Dose Range (a,b)	Control Limits (c)	
					Positive, %	Negative, %
A	X or gamma	-	<0.05 MeV ^(d)	50 mrems - 25 rems	100	30
B	X or gamma	1	0.05 - 0.2 MeV	50 mrems - 100 rems	100	30
		2	>0.2 - 3 MeV	50 mrems - 800 rems	40	30
C	Beta	1	Uranium	50 mrems - 10 rems	30	30
		2	>0.5 MeV max. energy (source other than uranium)	50 mrems - 800 rems	100	50
D	Neutron	1	<0.04 eV (thermal)	125 mrems - 100 rems	200 ^(e)	50 ^(e)
		2	1 - 10 MeV (fast)	125 mrems - 10 rems	50 ^(f)	50 ^(f)
E	Mixed	-	Any combination B,C,D	100 mrems - 100 rems	200 ^(g)	50 ^(g)

(a) Ranges given do not imply that dosimetry in ranges above or below these values is undesired or unusable, but only that appropriate control limits may be different outside these ranges.

(b) Dose ranges are based on the following RSE values:

Type of Radiation	RSE
X or gamma	1
Beta	1
Neutrons: (NBS Handbook 63, Table 2, p. 15)	

Energy - MeV	
Thermal	3
0.0001	2
0.005	2.5
0.02	5
0.1	8
0.5	10
1	10.5
2.5	8
5	7
7.5	7
10	6.5

(c) Selected values, within which averaged experimental results are expected to fall with statistical accuracy. For example, if the calibration exposure is 100 mrems beta plus 100% minus 50%, then the film dosimetry service's averaged findings should be within the band of 50 to 200 mrems with an acceptable statistical probability.

(d) Radiation spectrum and/or source of radiation is positively identified and used as basis for calibration.

(e) Provided the gamma ray dose does not exceed the thermal neutron dose.

(f) Provided the gamma ray dose does not exceed 1 roentgen.

(g) Provided source is unknown. Otherwise, subject to control limits in Classes B, C, D according to types of radiation encountered.

APPENDIX B
STATISTICAL AND EXPERIMENTAL STUDIES

APPENDIX B

STATISTICAL AND EXPERIMENTAL STUDIES⁽⁹⁻¹⁵⁾1. INTRODUCTION

A common statistical approach to the study of measurement processes employs the concept of a probability distribution representing an infinite set of measurements. That is, the quantities resulting from a large number of measurements made on a single "object" with a well controlled process may be summarized in a histogram with the purpose of providing information about the measurement process. The theoretical counterpart of the histogram is the probability distribution. A histogram and a probability distribution are illustrated in Figure B-1.

FIGURE B-1. *Histogram and Probability Distribution*

The histogram is a graphical display of the proportions of measurements of the quantity μ (the value associated with the single object measured) which fall into several intervals about μ . The probability distribution is represented by a mathematical

function which, when integrated over any interval about μ , yields a value that is the limit of the sequence of proportions of measurements falling in that interval as the number of measurements becomes very large.

In judging the quality of a measurement process or in comparing the qualities of two or more measurement processes, several features of their associated probability distributions may be of interest. The difference between μ and some defined center of the distribution, the range over which the distribution spreads, the lack of symmetry in the distribution, and the number of peaks in the distribution are a few features which may be of interest. Whether or not these features or others play a part in defining the quality of a measurement process often depends on the particular use to be made of the measurements. However, at least two seem to be of sufficient general interest to warrant special attention: the difference between the "center" of the distribution and μ (systematic bias), and the dispersion of the measurements or spread of the distribution (variance). In the remainder of this Appendix these two features will be referred to simply as bias and variance. Other terms that are frequently used for these features are accuracy and precision.

2. PROBABILITY DISTRIBUTIONS

Some probability distributions can be represented by probability density functions. For example, the normal (or Gaussian) distribution is represented by the two parameter probability density function

$$f(x) = \frac{1}{\sqrt{2\pi} \sigma} e^{-(x-\xi)^2/2\sigma^2} . \quad (B-1)$$

This function is defined for all real values of x , and is symmetric about ξ as shown in Figure B-2.

FIGURE B-2. Normal Probability Density Function

The location of the distribution is determined by ξ , and its spread (variance) by σ^2 . The mathematical definitions for the mean and variance of a probability distribution are

$$\text{Mean} = \theta = \int_{-\infty}^{\infty} xf(x) dx \quad (\text{B-2})$$

and

$$\text{Variance} = \int_{-\infty}^{\infty} (x-\theta)^2 f(x) dx, \quad (\text{B-3})$$

where $f(x)$ is the probability density function. In the case of the normal distribution shown in Figure B-2, the mean equals ξ and the variance equals σ^2 . Bias, as used here, is defined to be

$$\text{Bias} = \text{Mean} - \mu = \int_{-\infty}^{\infty} xf(x) dx - \mu, \quad (\text{B-4})$$

where μ equals the quantity being measured.

A function of Statistics is to provide estimates of the values of the mean and variance from a sample of measurements whose process is conceived of as being represented by a probability distribution. If $X_1, X_2, \dots, X_n$ is a sample of measurements on a single object, then the

$$\text{Sample mean} = \bar{x} = \frac{\sum_{i=1}^n X_i}{n} \quad (\text{B-5})$$

and

$$\text{Sample variance} = S^2 = \frac{\sum_{i=1}^n (X_i - \bar{x})^2}{(n-1)} \quad (\text{B-6})$$

are unbiased estimates of the mean and variance. An unbiased estimate of the bias is

$$\text{Sample estimate of bias} = \bar{x} - \mu. \quad (\text{B-7})$$

3. A CASE STUDY

Information about a probability distribution can be obtained by studying the histogram constructed and estimates computed from a number of measurements. In the case of information about the form of the probability density function, large samples are the most useful. Some large "samples" for a film badge dosimetry measurement process were available from records of the Hanford film badge dosimeter for the period 1950 to 1964.

The Hanford calibrations records include more than 600 "measurements" on each of several exposure levels of gamma, beta, and 17 keV X-ray radiations. The data are densities that were used for computing calibration curves, and measurements (estimated exposures) computed from those densities by using their associated calibration curves. Densities and measurements for each exposure level were assumed to be random

samples from populations of measurements at that level. It should be borne in mind that these data are routine records and not experimental data, so that the probability model is not as well satisfied as in that latter case. The intent of the analysis is to provide suggestions about probability distribution features of film badge dosimetry processes in general rather than to provide conclusions about a particular process.

The records studied were for eleven exposure levels of gamma, eleven for beta, and eight for X-ray radiation. Histograms for a few levels of gamma radiation over the range studied are depicted in Figure B-3.

These figures are for exposure levels, μ , of 30, 180, and 500 mrem. There is an apparent negative bias at these levels indicated by the excess of measurements being less than μ . Also, there is some indication that the variance of the distributions increases with μ . Quantitative evidence of these features is presented in Table B-I.

This table lists the sample mean, $\bar{x}$, and sample variance, S^2 , for measurement samples at different levels of μ . The variances tend to increase with μ , while the "relative error," $(2S/\bar{x})100(\%)$, tends to decrease with μ for $\mu \geq 30$ mrem. "T" tests for differences between the $\bar{x}$'s (means of the measurements) and μ 's are significant at the confidence levels indicated, showing that there are biases in the gamma and beta measurements. These tests are only approximate since as, shown below, the measurements are not normally distributed. The "relative bias," $(\bar{x}-\mu)100/\bar{x}(\%)$, is small compared to the "relative error" due to random variation. This suggests that the variance feature of film badge dosimetry measurements may be the major concern. An investigation of the film badge dosimetry industry (discussed later) showed that bias is more of a concern than indicated in this case study.

FIGURE B-3. *Histograms at Three Exposure Levels of Radium Gamma Radiation*

TABLE B-I. Bias and Variance Features for Hanford Film
Badge Dosimetry Measurement Records

Type of Radiation	Exposure = μ (mrem)	$\bar{x}$	S^2	$\left(\frac{2S}{\bar{x}}\right)100(\%)$	% Measurements $w_n \pm 2 S$	$T = \frac{\sqrt{n} (\bar{x} - \mu)}{S}$	$\left(\frac{\bar{x} - \mu}{\bar{x}}\right)100(\%)$
Gamma	0	5.18	124.59	430	95.4	+ 12.04(a)	100.0
	15	14.50	181.03	186	99.0	- 0.96	- 3.4
	30	29.53	26.65	35	94.3	- 2.38(b)	- 1.6
	60	57.96	31.36	19	95.8	- 9.46(a)	- 3.5
	90	88.87	36.86	14	96.0	- 4.83(a)	- 1.3
	120	120.74	36.17	10	95.0	+ 3.21(a)	0.6
	180	179.24	51.19	8	97.6	- 2.74(a)	- 0.4
	240	237.72	49.10	6	95.7	- 8.42(a)	- 1.0
	300	301.46	57.72	5	96.0	+ 4.97(a)	0.5
	500	499.36	92.69	4	99.1	- 1.73	- 0.1
	750	749.82	7.59	0.7	99.1	- 1.65	- 0.02
Beta	0	9.03	430.78	460	97.3	+ 11.27(a)	100.0
	15	14.31	95.89	137	95.7	- 1.81	- 4.8
	30	30.42	80.07	59	95.1	+ 1.23	1.4
	60	59.09	81.53	31	95.8	- 2.60(a)	- 1.5
	90	87.30	110.09	24	94.6	- 6.67(a)	- 3.1
	120	117.88	110.31	18	96.3	- 5.23(a)	- 1.8
	180	178.15	203.01	16	97.6	- 3.36(a)	- 1.0
	240	241.12	209.34	12	96.7	+ 2.00(b)	0.5
	300	298.93	293.07	12	94.2	- 1.62	- 0.4
	500	498.55	175.52	5	96.6	- 2.83(a)	- 0.3
	750	749.46	31.12	1	98.8	- 2.53(b)	- 0.07
X-ray	0	-9.49	2.52	-34	96.6	- 1.55	100.0
	10	10.13	2.05	28	95.8	+ 0.24	1.3
	20	20.34	3.07	17	94.9	+ 0.50	1.7
	40	39.85	4.71	11	95.7	- 1.80	- 0.4
	60	59.93	5.57	8	96.0	- 0.78	- 0.1
	80	79.68	11.03	8	96.6	- 0.10	- 0.4
	120	120.27	5.61	4	96.4	+ 0.03	0.2
	160	159.60	8.40	4	99.0	- 3.60(a)	- 0.3

(a) Significant difference at the 99% confidence level.

(b) Significant difference at the 95% confidence level.

As stated above, large samples are the most useful for studying the form of the underlying probability distribution. This was one of the reasons for analyzing the Hanford records. It would be convenient if one could assume that film badge dosimetry measurements were normally distributed. Consequently, tests for normality were computed from these data. The χ^2 test for goodness of fit, and estimates of the coefficient of skewness, γ_1 , and the coefficient of excess, γ_2 , were computed (see reference (10), pp. 187, 437-41). In order for these tests to support the normality hypothesis, χ^2 (19 degrees of freedom) should be less than 25, $\hat{\gamma}_1 \approx 0$ and $\hat{\gamma}_2 \approx 0$. Values for these statistics for measurement data are presented in Table B-II.

*TABLE B-II. Skewness and Excess Features
for Hanford Film Badge Dosimetry
Measurement Records*

Type of Radiation	Exposure = μ (mrem)	χ^2	$\hat{\gamma}_1$	$\hat{\gamma}_2$
Gamma	0	99.9	1.78	7.70
	15	657.4	12.86	220.44
	30	48.1	0.77	2.87
	60	81.8	1.57	7.51
	90	54.7	- 1.02	6.19
	120	67.4	- 0.78	8.33
	180	112.3	- 2.86	27.19
	240	19.3	- 0.80	6.12
	300	40.0	- 1.16	13.93
	500	772.1	-12.74	312.80
Beta	750	1,453.3	-71.51	28,227.25
	0	252.8	5.55	52.16
	15	21.0	0.99	3.14
	30	28.5	0.75	1.53
	60	16.2	- 0.10	2.48
	90	22.3	- 0.44	3.63
	120	18.5	- 0.23	1.15
	180	125.2	0.17	43.12
	240	70.3	0.18	15.03
	300	45.9	- 0.03	5.82
X-ray	500	359.1	- 2.86	46.59
	750	1,575.3	-20.27	1,285.60
	0	85.0	2.28	16.45
	10	48.4	0.91	3.74
	20	19.5	- 0.28	1.78
	40	43.2	- 0.23	7.48
	60	16.2	- 0.05	3.44
	80	58.6	2.84	29.08
	120	113.0	2.31	27.20
	160	2,391.9	- 7.99	166.14

The χ^2 test rejects the hypothesis of normality in all but one of the gamma cases, in seven out of eleven of the beta cases, and in six of the eight X-ray cases. Negative values for $\hat{\gamma}_1$ indicate a long tail to the left, and positive values a long tail to the right. The greatest deviation from normality appears to be an excess in the mode as evidenced by the positive values of $\hat{\gamma}_2$. The histogram for estimated exposure at the 60 mrem gamma level and a superimposed "normal histogram" are shown in Figure B-4.

FIGURE B-4. Histograms for Radium Gamma Measurements and Normal Distribution

Similar analyses were performed on the film badge dosimetry density records. The estimates for variance, χ^2 , skewness and excess are shown in Table B-III. Estimates for the zero exposure level were not computed since all densities were adjusted to zero at that level.

TABLE B-III. *Variance, Skewness and Excess Features for Hanford Film Badge Dosimetry Density Records*

Type of Radiation	Exposure = μ (mrem)	S^2	χ^2	$\hat{\gamma}_1$	$\hat{\gamma}_2$
Gamma	15	8.22	400.4	9.17	161.55
	30	3.49	71.8	-0.34	4.14
	60	3.76	98.7	-0.10	2.61
	90	4.48	67.4	0.09	2.04
	120	4.97	68.9	0.16	1.64
	180	6.82	34.7	0.16	1.28
	240	8.79	97.9	0.45	0.48
	300	11.13	40.1	0.34	0.11
	500	21.91	88.9	0.42	0.13
Beta	750	40.32	45.5	0.00	0.04
	15	2.10	292.2	-7.11	82.85
	30	2.30	252.0	-6.26	68.34
	60	2.43	236.3	-6.31	70.39
	90	2.83	225.7	-4.54	38.90
	120	2.26	208.5	-3.05	28.99
	180	3.25	173.4	-0.52	18.51
	240	4.09	94.5	-0.86	16.15
	300	5.03	56.7	-0.63	11.26
X-ray	500	8.09	68.9	1.90	10.93
	750	20.28	39.9	-0.11	13.25
	10	0.37	233.0	4.11	32.51
	20	0.59	117.6	-1.19	44.90
	40	1.21	78.4	-1.71	34.38
	60	1.50	55.0	0.86	1.85
	80	2.57	12.7	0.55	0.94
	120	8.24	72.1	-3.02	45.49
	160	10.18	33.1	0.00	5.43

The tendency of variance to be strictly increasing above the 30 mrem exposure level is more evident in the density data than in the measurement data. This is especially noticeable at the highest exposure levels where the density variances are the highest, but the measurement variances drop sharply. The χ^2 tests of normality were all significant except at one exposure level of X-ray radiation. Skewness and excess are less marked for gamma radiation densities than for gamma measurements. For beta and X-ray densities, skewness and excess are more

pronounced than for measurements at the lower exposure levels, and less pronounced at the higher levels.

It is conjectured that these differences in distribution features for the two sets of data are largely due to the calibration curves used to generate measurements from densities. The calibration curves computed from these data were least square cubic polynomials of density on exposure level. If linear curves had been fit, one would expect the estimates of distribution features to be more alike.

In general, then, film badge dosimetry measurements for gamma, beta and 17 keV X-ray radiation types should not be expected to be normally distributed at all exposure levels. The variance of the measurements may increase with exposure level, and biases may exist and be of different magnitudes at different exposure levels.

4. INDUSTRY STUDY

From the information obtained in the study of the Hanford records a model for film badge dosimetry measurements was constructed and small sample experiments for investigating film badge processes throughout the United States were designed. The purpose of these experiments was to estimate the bias and variance parameters characterizing the many processes in use with a view to analyzing these estimates and synthesizing performance criteria and testing procedures aimed at improving film badge dosimetry measurements.

A measurement, D , at a given exposure level, E , was assumed to be described by the equation

$$D = \alpha + \beta E + \epsilon_E, \quad (B-8)$$

where α and β are constant bias parameters and ϵ_E is a random variable having mean zero and variance σ_E^2 . The measurement D has an associated probability distribution with mean $\alpha + \beta E$, variance σ_E^2 , and bias $\alpha + \beta E - E = \alpha + (\beta - 1)E$. The choice of a linear bias relationship between measurements and exposure

level was based on its possible broad application to many processes, and should not be construed as being descriptive of the true bias situation for every film badge dosimetry process. A detailed study may suggest some other bias relationship for a particular process. The linear assumption includes processes with zero bias ($\alpha = 0$, $\beta = 1$), with additive bias ($\alpha \neq 0$), and with multiplicative bias ($\beta \neq 1$).

There are many potential sources of bias inherent in a film badge dosimetry measurement process, though the suspected major source is the calibration procedure. Sources of bias can often be detected and "removed," but sources of "random variation" (parameterized by σ_E^2), such as those introduced by differences in film emulsions, shield thicknesses, storage practices and density readings, are not always susceptible to removal by the processor. However, the minimization of the effects of these sources of variation is part of the process control responsibility.

To illustrate how a process can have a bias $\alpha \neq 0$ we consider the use of a multiposition-fixed time calibration technique with a least squares fit linear calibration curve, $\Delta = c + dE$, of density Δ on exposure E . If the instrument readings of the exposure levels E_i are each a positive quantity δ too low because of miscalibration of the instrument, then the true exposures are $E_i + \delta$. The processor computes

$$d = \frac{\sum (\Delta_i - \bar{\Delta}) E_i}{\sum (E_i - \bar{E})^2} \quad (B-9)$$

and

$$c = \bar{\Delta} - d\bar{E}, \quad (B-10)$$

when computations should be

$$\begin{aligned}
 d' &= \frac{\sum (\Delta_i - \bar{\Delta}) (E_i + \delta)}{\sum (E_i + \delta - \bar{E} - \delta)^2} = \frac{\sum (\Delta_i - \bar{\Delta}) E_i + \delta \sum (\Delta_i - \bar{\Delta})}{\sum (E_i - \bar{E})^2} \\
 &= \frac{\sum (\Delta_i - \bar{\Delta}) E_i}{\sum (E_i - \bar{E})^2} = d
 \end{aligned} \tag{B-11}$$

and

$$c' = \bar{\Delta} - d' (\bar{E} + \delta) = \bar{\Delta} - d\bar{E} - d\delta = c - d\delta. \tag{B-12}$$

When the processor then estimates an exposure from a density Δ with his calibration curve he computes the measurement

$$\hat{D} = \frac{\Delta - c}{d}, \tag{B-13}$$

when it should be

$$\tilde{D} = \frac{\Delta - c + d\delta}{d} = \hat{D} + \delta. \tag{B-14}$$

The measurement $\hat{D}$ is a constant quantity δ too low at all exposure levels, thus giving rise to an $\alpha < 0$.

An example of a process with a $\beta \neq 1$ is the same situation as above except the calibration technique uses fixed position-variable time exposures. In this case the exposures E_i are computed as

$E_i = (E/t)t_i$ where t_i is the length of exposure time, while the E_i should be

$$E_i = [(E + \delta)/t]t_i. \tag{B-15}$$

The parameter estimates are

$$d = \frac{\sum (\Delta_i - \bar{\Delta}) (E/t)t_i}{\sum [(E/t)t_i - (E/t)\bar{t}]^2} = \frac{\sum (\Delta_i - \bar{\Delta}) t_i}{(E/t) \sum (t_i - \bar{t})^2} \tag{B-16}$$

and

$$c = \bar{\Delta} - d(E/t)\bar{t} = \bar{\Delta} - \frac{\sum(\Delta_i - \bar{\Delta})t_i}{\sum(t_i - \bar{t})^2} \bar{t} ; \quad (B-17)$$

and should be

$$\begin{aligned} d' &= \frac{\sum(\Delta_i - \bar{\Delta})[(E+\delta)/t]t_i}{\sum\{[(E+\delta)/t]t_i - [(E+\delta)/t]\bar{t}\}^2} \\ &= \frac{\sum(\Delta_i - \bar{\Delta})t_i}{[(E+\delta)/t]\sum(t_i - \bar{t})^2} < d , \end{aligned} \quad (B-18)$$

and

$$c' = \bar{\Delta} - d'[(E+\delta)/t]\bar{t} = \bar{\Delta} - \frac{\sum(\Delta_i - \bar{\Delta})t_i}{\sum(t_i - \bar{t})^2} \bar{t} = c. \quad (B-19)$$

Measurements are

$$\hat{D} = \frac{\Delta - c}{d} , \quad (B-20)$$

and should be

$$\hat{D} = \frac{\Delta - c}{d'} ; \quad (B-21)$$

and, since $d' < d$, are proportionally too low at all exposure levels giving rise to a $\beta < 1$.

These two examples and the varying bias observed in the study of the Hanford records provide the justification for the assumed linear relationship between measurement bias and exposure level. If the bias inherent in a particular process is related to exposure level in a nonlinear fashion, it is still very likely that it will be detected by an analysis under the linear assumption. For example, a linear fit to data that are higher degree polynomial or exponential in nature will often yield evidence of a non-zero intercept and a non-zero slope. Thus, in an

analysis of film dosimetry measurements, detection of a linear bias may have its greatest value in the fact that it indicates some sort of bias and suggests to the processor that he should investigate his process.

To estimate bias and variance parameters in film badge dosimetry processes, data were obtained through the cooperation of 35 processors. Nine types of radiation exposures were applied to sets of badges submitted by the processors. Not all processors participated for all radiation types. Those that did submitted 218 badges which were allocated to exposure levels as shown in Table B-IV.

TABLE B-IV. Number of Badges Exposed for Each Processor in the Industry Study

Type of Exposure (Source)	Exposure (rem) and Number of Badges				
Radium (Ra)	0.060 4	0.120 4	0.240 6	0.500 6	1.000 8
⁶⁰ Co	40 4		100 8		600 12
170 keV X-ray	0.060 4	0.120 4	0.240 6	0.500 6	1.000 8
100 keV X-ray	0.060 4	0.120 4	0.240 6	0.500 6	1.000 8
17 keV X-ray	0.060 4		0.120 4		0.240 6
Uranium (U)	0.120 4		0.240 8		0.500 8
Ra-U Mixture	0.120/0.120 4		0.240/0.240 8		0.500/0.500 8
Ra-17 keV X-ray Mixture	0.120/0.120 4		0.240/0.240 8		0.500/0.500 8
Thermal Neutrons- Sigma Pile	0.060 4		0.120 4		0.382 4
Fast Neutrons- PuBe	0.200 4		0.262 8		0.787 12

Except for thermal neutron exposures, the increasing number of badges with exposure level within a radiation type were, in part, selected on the basis of variance considerations. Recognizing that the variance of the measurements would possibly increase with exposure level, larger numbers of badges were assigned to the higher levels in order to reduce the variance of the $\bar{D}$ and S^2 statistics computed from the data.

Initially, the sample sizes considered were based on trying to obtain equal variance for the S^2 statistics within a radiation type, but this led to a total number of badges that was judged to be unreasonable. For example, assuming normally distributed measurements, the variance of S^2 is $\frac{2\sigma^4}{n-1}$ where σ^4 is the square of the variance of the measurements; and using $(S^2)^2$ values from the Hanford data (Table B-I; Section 3.) to estimate σ^4 , let

$$\frac{2S_1^4}{n_1-1} = \frac{2S_2^4}{n_2-1} = \frac{2S_3^4}{n_3-1} = \frac{2S_4^4}{n_4-1} ,$$

where the n_i 's are the desired sample sizes for the 0.060, 0.120, 0.240, and 0.500 rem exposure levels of radium gamma radiation. Then choosing $n_1=4$ as the smallest sample size results in $n_2=8$, $n_3=15$, and $n_4=54$ as the sample sizes for the other exposure levels. It was decided that this would be an excessive number of badges to consider. Consequently, the final allotment of badges was determined by assigning a reasonable number to each radiation type and exposing more at the high exposure levels than at the low levels.

For some radiation types the sample sizes displayed in Table B-IV come close to stabilizing the variance of the sample means. The variance of a sample mean is $\frac{\sigma^2}{n}$. If the Hanford data is again used as a guide, the sample sizes for equalizing the variances of the means for radium gamma radiation are $n_1=4$, $n_2=5$, $n_3=6$, and $n_4=12$.

Each processor numbered his film badges according to a specified set of numbers for each type of radiation exposure. Within each type of radiation exposure the badges were assigned to exposure levels at random. Exposures were accomplished in Battelle-Northwest facilities at Richland, Washington, and badges were returned to the processors for evaluation. Processors then sent their measurement data to Battelle-Northwest for analysis.

The first step in the reduction of data for purposes of estimating the bias and variance inherent in film badge dosimetry measurements involved computing sample means, $\bar{D}$, and sample variances, S^2 , at each exposure level E . For each radiation type we introduce the subscript i on the sample size n , $\bar{D}$, S^2 and E to denote the exposure level: e.g., for radium gamma exposures $E_1 = 60$, $E_2 = 120$, $E_3 = 240$, $E_4 = 500$ and $E_5 = 1000$ mrem. From the description of a single measurement given at the beginning of this Section, the description of a sample mean is taken to be:

$$\bar{D}_i = \alpha + \beta E_i + \epsilon_i, \quad (B-22)$$

where α and β are the bias parameters and ϵ_i is a random variable with mean zero and variance $\sigma_{E_i}^2/n_i$.

S_i^2/n_i is an unbiased estimate of $\sigma_{E_i}^2/n_i$. Using $w_i = (S_i^2/n_i)^{-1}$ as "weights," the following weighted least square estimates of α and β were computed for each process and radiation type:

$$a = \left(\sum_{i=1}^m w_i \bar{D}_i / \sum_{i=1}^m w_i \right) - b \left(\sum_{i=1}^m w_i E_i / \sum_{i=1}^m w_i \right), \quad (B-23)$$

$$b = \frac{\sum_{i=1}^m w_i \bar{D}_i E_i - \left[\left(\sum_{i=1}^m w_i \bar{D}_i \right) \left(\sum_{i=1}^m w_i E_i \right) / \sum_{i=1}^m w_i \right]}{\sum_{i=1}^m w_i E_i^2 - \left[\left(\sum_{i=1}^m w_i E_i \right)^2 / \sum_{i=1}^m w_i \right]} \quad (B-24)$$

where m denotes the number of exposure levels within the radiation type.

The computations in Equations (B-23, B-24) involve division by the S_i^2 estimates. Out of 1133 S_i^2 estimates in the industry study, 107 had zero values due to excessive rounding. In most cases this was caused by rounding the measurements to centirems rather than millirems, but for the high exposures in the ^{60}Co radiation type it was usually due to rounding to rems rather than decirems. To carry out the computations in Equations (B-23, B-24) the zero values for S_i^2 in all radiation types except ^{60}Co were assigned the value 25, and for the ^{60}Co data were assigned the value 250,000. The rationale underlying these assignments is as follows: if the exposure estimates at a single exposure level are assumed to have an associated discrete probability distribution with equal probability (1/2) at two points $h(0.01)$ and $(h+1)(0.01)$ where h is in rems (h and $h+1$ for ^{60}Co data), then the variance of that distribution equals 25 mrem^2 ($250,000 \text{ mrem}^2$ for ^{60}Co data). The rounding procedure is further discussed in Section 5, Appendix B.

The estimates, a and b , for each process and radiation type were used to test the hypotheses $H_0^1 : \alpha=0$ and $H_0^2 : \beta=1$ versus the alternatives $H_A^1 : \alpha \neq 0$ and $H_A^2 : \beta \neq 1$. If the $\sigma_{E_i}^2$'s were known and $w'_i = n_i/\sigma_{E_i}^2$ substituted for w_i in Equations (B-23, B-24) then a and b would be approximately normally distributed random variables with respective means α and β and variances

$$\sigma_a^2 = \left(\sum_{i=1}^m w'_i E_i^2 / \sum_{i=1}^m w'_i \right) \sigma_b^2, \quad (\text{B-25})$$

and

$$\sigma_b^2 = \left\{ \sum_{i=1}^m w'_i E_i^2 - \left[\left(\sum_{i=1}^m w'_i E_i \right)^2 / \sum_{i=1}^m w'_i \right] \right\}^{-1}. \quad (\text{B-26})$$

Estimates for these variances, $\hat{\sigma}_a^2$ and $\hat{\sigma}_b^2$, were computed by substituting w_i for w_i' in Equations (B-25, B-26). The hypothesis H_0^1 was rejected if

$$\frac{|a|}{\hat{\sigma}_a} > 1.96; \quad (B-27)$$

the hypothesis H_0^2 was rejected if

$$\frac{|b-1|}{\hat{\sigma}_b} > 1.96, \quad (B-28)$$

These 5% significance level tests are based on the assumption that the sample means, $\bar{D}_i$, are approximately normally distributed. The interpretation of the 5% significance level is that the inequalities in Equations (B-27, B-28) will each hold 5% of the time when $\alpha=0$ and $\beta=1$.

In the Industry Study, there were 319 tests each of H_0^1 and H_0^2 . The range of the a and b estimates and the number of hypotheses rejected are indicated in Table B-V. The 13 radiation types shown resulted from analyzing the two mixture radiation types as five separate groups of data.

In order to illustrate the meaning of the bias estimates, the 100 keV X-ray sample means for the process with $b = 0.29$ are plotted in Figure B-5.

The negative multiplicative bias for this process is outstanding. All other processes investigated that had negative multiplicative biases for this radiation type were less extreme.

TABLE B-V. *Ranges of Bias Estimates and Results of Tests of Hypotheses for Each Radiation Type*

<u>Radiation Type</u>	<u>Number of Processors</u>	<u>a</u> <u>Range (mrem)</u>		<u>b</u> <u>Range</u>		<u>No. of $\alpha \neq 0$</u>	<u>No. of $\beta \neq 1$</u>
Radium (Ra)	34	-49	57	0.54	1.17	27	33
^{60}Co	33	-19,059	48,476	0	1.48	28	32
170 keV X-ray	27	-61	207	0.32	1.82	20	25
100 keV X-ray	27	-54	141	0.29	3.20	18	24
17 keV X-ray	23	-20	38	0.01	2.46	17	21
Uranium (U)	31	-93	46	0.56	2.64	19	29
γ from Ra and U mix.	31	-51	70	0.60	1.32	22	24
β from Ra and U mix.	31	-87	74	0.20	2.49	23	30
γ from Ra and 17 keV X-ray mix.	17	-77	42	0.73	1.92	16	14
X-ray from Ra and 17 keV X-ray mix.	13	-138	119	0.15	12.39	9	11
γ + X-ray from Ra and 17 keV X-ray mix.	9	-73	103	0.40	1.04	8	8
Thermal Neutrons	16	-61	582	0.16	7.33	9	15
Fast Neutrons	27	-139	552	0.03	2.59	10	20

FIGURE B-5. *Plot of Sample Means for Process with Lowest b for the Photon-Radiation Category, Intermediate Energy*

The last two columns of Table B-V give the numbers of processors with $\alpha \neq 0$ or $\beta \neq 1$. There is evidence for 71% of the α 's tested not being equal to 0, and 89% of the β 's tested not being equal to 1. Furthermore, it appears likely that some processors have biases that were not detected here due to insufficient data. For example, tests for $\alpha = 0$ from the fast neutron radiation data detected only 10 out of 27 processors with $\alpha \neq 0$, but ranked a estimates, and an average variance of these estimates equal to 2745 (mrem)^2 suggests that additional data would detect more α 's not equal to zero.

The weighted least squares estimates of the bias parameters required the S_i^2 estimates of the variance $\sigma_{E_i}^2$ at each exposure level E_i for each process and each radiation type. An additional purpose for computing these estimates was to see if any generalization regarding the variance as a function of exposure level could be made for the whole film badge dosimetry measurement industry. If some specific functional form was characteristic of all processes, then that form would be appropriate for a Film Dosimeter Calibration Laboratory to use as a criteria for variance magnitudes that would provide effective tests over a range of exposures for many processes. A tally of the number of processes with variance estimates exhibiting various functional features is given in Table B-VI.

From the data in the first four columns, it appears that no particular functional form is dominant for any radiation type except possibly the strictly increasing form for ^{60}Co . For 11 of the 13 radiation types, the strictly increasing form column lists more processes than any other column. It is apparent that no specific functional form describes the variance-exposure relationship for all processes in any radiation type.

TABLE B-VI. Number of Processes with Indicated Features of Variance (S^2) as a Function of Exposure Level

Radiation Type	"Convex Upward"	"Convex Downward"	Irregular or	$\uparrow$ or	(a) $S_L^2 < S_U^2$	$S_L^2 > S_U^2$	$\frac{S_L}{E_L} < \frac{S_U}{E_U}$	$\frac{S_L}{E_L} > \frac{S_U}{E_U}$
Ra	4	1	20	9	32	2	1	33
^{60}Co	4	1	-	28	32	1	19	14
170 keV X-ray	8	1	8	10	26	1	5	22
100 keV X-ray	2	1	6	18	24	3	9	18
17 keV X-ray	6	5	-	12	19	4	5	18
U	13	9	-	9	26	5	2	29
γ from Ra and U mix.	7	8	-	16	28	3	1	30
β from Ra and U mix.	6	9	-	16	23	8	4	27
γ from Ra and 17 keV X-ray mix.	4	6	-	7	11	6	1	16
X-ray from Ra and 17 keV X-ray mix.	3	0	-	10	12	1	7	6
γ +X from Ra and 17 keV X-ray mix.	0	3	-	6	9	0	3	6
Thermal Neutrons	2	5	-	9	11	5	2	14
Fast Neutrons ^(b)	7	1	-	18	26	1	11	16

(a) S_L^2 = Sample variance at lowest exposure level.

S_U^2 = Sample variance at highest exposure level.

(b) The S^2 estimates for one process were strictly decreasing.

A class of strictly increasing functional forms that may provide effective test criteria over most of the exposure range for most processes is specified by the relationship $\sigma_E^2 = \kappa E^\mu$; $\mu > 0$ and $\kappa > 0$. The data in columns four through eight were tabulated for the purpose of aiding in the selection of μ values in the above equation. Columns four and five emphasize the fact that for most of the processes studied the variance at the highest exposure level is apparently greater than the variance at the lowest exposure level. Columns seven and eight indicate that the relative variation, $\frac{\sigma_E}{E}$, is lower at the highest exposure level than at the lowest exposure level for most processes and radiation types except for ^{60}Co , X-ray (Radium and 17 keV X-ray mixture), and fast neutron radiation types where the number of processes with decreasing relative variation is more nearly equal to the number of processes with increasing relative variation. This suggests that for ^{60}Co , X-ray (Radium and 17 keV X-ray mixture), and fast neutron radiation types $\sigma_E^2 = \kappa E^2$ may be an effective functional form subclass to choose, since, for this choice, σ_E^2 increases with E and $\frac{\sigma_E}{E}$ is constant for all E .

For all other radiation types, $\sigma_E^2 = \kappa E^\mu$ where $0 < \mu < 2$ may be effective since (for this subclass) σ_E^2 increases with E and $\frac{\sigma_E}{E}$ decreases with E . In this latter case there is a benefit

in testing that accrues from choosing $\mu = 1$; hence, the subclass specified by $\sigma_E^2 = \kappa E$ was chosen for developing criteria for those radiation types.

All data and some estimates from this study are contained in a separate data summary which is not a part of this report since it contains the detailed performance data of each participating processor. It is intended that these data be kept on file for possible future analyses and use by any Film Dosimetry Calibration Laboratory that may be established. For example, the following question can be posed: are there any significant

differences in bias parameters for Radium gamma measurements when ^{60}Co or ^{137}Cs calibration sources are used instead of a Radium calibration source? The answer to this question would indicate whether or not it is necessary to use exposure and calibration sources that are similar in bias estimation experiments.

From the information obtained in the Industry Study, it was determined that six processes used Radium, four processes used ^{137}Cs and twelve processes used ^{60}Co calibration sources for evaluating high energy gamma exposures. The mean of the α 's and the mean of the β 's for each group were estimated. The Radium group means were compared to the ^{137}Cs group means and the ^{60}Co group means using an unbiased estimate of the variance of the comparison. These approximate tests did not detect significant differences between β means, but did detect significant differences between α means. ^{137}Cs and ^{60}Co group α means appear to be larger than the Radium group α mean.

Since many factors among these groups other than calibration source vary, the results obtained above should be interpreted with caution. Perhaps some other factor is the cause of the noted differences in the α means. The value of the comparisons made here is that they suggest a need for experiments designed specifically to answer the question posed. If no significant differences in the α means had been detected, the need for experimentation would not receive as high a priority.

For other questions arising, tentative answers may be found in analyses of these data. They constitute a valuable source for preliminary investigations.

The conclusion drawn from the study of bias in the film badge dosimetry measurement industry is that a national scope laboratory could fruitfully serve by performing a bias-correction function for the industry. The variance analysis suggests that

the nature of the random variation over a range of exposure levels may be quite different for different processes. Hence, any single variance-exposure level relationship established as a criterion to be used in a national laboratory testing procedure may not be effective over the whole range of exposures for all processes. That is, some processes will be more susceptible than others to test failure for low level exposures while the situation may reverse for high level exposures. However, a criterion choice that seems to be a reasonable compromise was made on the basis of the variance analysis.

The derivations of test procedures recommended for use by a Film Dosimetry Calibrations Laboratory are contained in the next section of this Appendix.

5. RECOMMENDED STATISTICAL TEST PROCEDURES

This Section contains the data collection and processing procedures recommended for use by the Film Dosimetry Calibrations Laboratory. Many of the procedures given here are similar to those used in the Industry Study discussed in Section 4; so computations specified there will be referred to by number rather than be repeated here. The topics in their order of discussion are as follows:

1. Data Collection
2. Rounding
3. Outlier Tests
4. Bias Tests
5. Bias Corrections
6. Variance Tests
7. Alternate Data Collection.

The recommended decision procedures associated with the test results are specified in Section 6 of this Appendix.

The Laboratory will require that a total of n film badges be submitted by a processor seeking approval of his process for a particular radiation type. At the discretion of the Laboratory Director, n can be any chosen number greater than 4, though it should not usually be less than 10 nor more than 30. The laboratory will expose sets containing n_i badges ($n_i \geq 2$) at m exposure levels E_i ($m \geq 2$), $i = 1, 2, \dots, m$ and $\sum_{i=1}^m n_i = n$.

Generally, these E_i 's should be within the range of exposure levels encompassed by the variance performance criteria developed. All n badges may be exposed and returned to the processor for evaluation as one group, or may be requested, exposed and evaluated over an extended period of time. In some cases, this latter procedure will introduce an among-calibration-curves component of variance not present in the Industry Study data. The effect of this will be to reduce the probability of passing the variance tests discussed later in this section.

In evaluating exposures, it would be desirable (from a performance analysis viewpoint) to have all processors report measurements up to one rem in units of millirem. At the present time many processors are rounding measurements below one rem to centirems. There are two reasons for suggesting the millirem unit--practical and theoretical.

The practical aspect of reporting to millirem is concerned with the computations to be made by the Laboratory in testing process variances. Economy requires that the tests be based on rather small sample sizes at each exposure level; hence, the chance of getting variance estimates equal to zero with present rounding procedures is high at low exposure levels. That is, rounding to centirems at low exposure levels is likely to produce n_i equal measurements simply because of the rounding, thus yielding data that gives no reflection of the process variance at that level and which presents problems in analysis. This occurred about one-tenth of the time in the Industry Study data, and if it should occur during Laboratory tests, two alternative solutions are suggested: (1) assign the value 25 mrem^2 ($250,000 \text{ mrem}^2$ for ^{60}Co) to S^2 , or (2) continue to obtain measurements until $S^2 \neq 0$.

On the theoretical side, it can be argued that for normally distributed measurements the probability of getting "closer to the true value" with one rounding procedure as opposed to another depends on the variance of the measurements. From the estimated variances of film badge dosimetry measurement processes in the zero to one rem range, the following example suggests that a "good" rounding unit would be millirems. Consider an unbiased measurement process represented by a normally distributed random variable X with mean μ and variance σ^2 . Let X_1 be a random variable defined by

$$P(X_1 = x) = P(x - 5 \leq X < x + 5) \text{ for } x = 10k, \quad (\text{B-29})$$

$$P(X_1 = x) = 0 \text{ for } x \neq 10k, \quad (\text{B-30})$$

where k is an integer; and let X_2 be a random variable defined by

$$P(X_2 = x) = P(x - 0.5 \leq X < x + 0.5) \text{ for } x = k, (\text{B-31})$$

$$P(X_2 = x) = 0 \text{ for } x \neq k, \quad (\text{B-32})$$

where k is an integer.

X_1 and X_2 represent the measurements rounded to the tens and the units digits, respectively. The probability that X_i "comes closer" to μ than x_j , $i \neq j$, is denoted

$$P_i(\mu, \sigma) = P(|X_i - \mu| < |X_j - \mu|) \quad . \quad (\text{B-33})$$

These probabilities are easily computed from normal probability tables. For example, if $0 \leq \mu \leq 0.5$, then

$$P_2(\mu, \sigma) = \sum_{y=0}^{\infty} \left[\Phi\left(\frac{10y + 9.5 - \mu}{\sigma}\right) + \Phi\left(\frac{10y + 9.5 + \mu}{\sigma}\right) - \Phi\left(\frac{10y + 5 - \mu}{\sigma}\right) - \Phi\left(\frac{10y + 5 + \mu}{\sigma}\right) \right] \quad , \quad (\text{B-34})$$

where

$$\Phi(x) = \int_{-\infty}^x \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx \quad (\text{B-35})$$

It is sufficient to consider μ values (the quantities measured) for $0 \leq \mu \leq 10$, and it is assumed here that these values are equally likely to occur; that is, μ is a uniformly distributed random variable between 0 and 10. Then, the probability that X_i "comes closer" to μ than X_j , $i \neq j$, is

$$P_i(\sigma) = \int_0^{10} [P_i(\mu, \sigma)/10] d\mu \quad . \quad (\text{B-36})$$

These probabilities have been approximated for $\sigma = 1(0.5)20$ and $\sigma = 30(10)100$ by approximating $P_i(\mu, \sigma)$ for $\mu = 0(0.5)5$ and computing

$$P_i(\sigma) = 1/20 P_i(0, \sigma) + 1/10 \cdot \sum_{i=1}^9 P_i(0.5i, \sigma) + 1/20 P_i(5, \sigma) \quad (B-37)$$

Some values of $P_i(\sigma)$ are given in Table B-VII. It appears that under this criterion, there would be considerable advantage to carrying the units digit when the standard deviation, σ , for the process is between zero and ten, and a lesser advantage when σ is greater than ten. It can be shown that the probabilities in Table B-VII are independent of the "adjacent" significant digits that are being compared, provided σ is in units of the additional significant digit. That is, the same results are obtained when comparing the tenths digit to the units digit, providing σ is multiplied by 0.1. This suggests the following rule: If $10^k \leq \sigma \leq 10^{k+1}$, then round to the nearest 10^k .

The Industry Study showed that 354 out of 1042 standard deviation estimates (S), in radiation types other than ^{60}Co , were less than ten millirems and greater than one millirem. This result suggests that there would be some benefit in rounding measurements less than one rem to millirems rather than centirems.

When all n measurements for a particular radiation type have been submitted to the Laboratory, then the following computations can be performed. Let

$$\begin{aligned} D_{ij} &= j^{\text{th}} \text{ measurement at exposure level } E_i, \\ i &= k, 2, \dots, m, \\ j &= 1, 2, \dots, n_i. \end{aligned}$$

Compute the sample mean and variance at each exposure level:

$$\bar{D}_i = \sum_{j=1}^{n_i} D_{ij} / n_i, \quad (B-38)$$

and

$$S_i^2 = \left[\sum_{j=1}^{n_i} D_{ij}^2 - \left(\sum_{j=1}^{n_i} D_{ij} \right)^2 / n_i \right] / (n_i - 1). \quad (B-39)$$

TABLE B-VII. Probabilities of "Coming Closer" Rounding to Tens Rather than to Units, P_1 and Rounding to Units Rather than to Tens, P_2

σ	$P_1(\sigma)$	$P_2(\sigma)$
1.0	0.1434	0.6387
2.0	0.2783	0.5351
3.0	0.3402	0.5004
4.0	0.3648	0.4917
6.0	0.3877	0.4833
8.0	0.4018	0.4762
10.0	0.4109	0.4713
15.0	0.4236	0.4645
20.0	0.4301	0.4609
30.0	0.4367	0.4573
40.0	0.4400	0.4555
50.0	0.4419	0.4545
70.0	0.4443	0.4530
100.0	0.4459	0.4522

In analyzing any set of data, there is the possibility that a discrepant measurement (outlier) will lead to poor decisions. Film badge dosimetry measurement data can contain outliers due to many sources: recording errors, damaged film and incorrect exposures are but a few. Some potential sources of outliers are not within the control of the processor, and, therefore, justify the inclusion of a test to remove outliers from the data prior to the bias and variance analyses. The following test⁽⁴⁾ is recommended:

1. For each exposure level E_i determine the D_{ij} (smallest or largest reported) that deviated most from $\bar{D}_i$;

2. Exclude that datum and compute a sample variance $S_i^{2'}$ from the remaining data;
3. Compute $S_i^{2'}/S_i^2$ and compare it to the critical value for sample size n_i given in Table B-VIII (note that at least three measurements are required);
4. If $S_i^{2'}/S_i^2$ is less than the critical value, then declare the extreme value to be an outlier.

TABLE B-VIII. *Critical Values for Outlier Test*

n_i	<u>Critical Value</u>
3	0.0027
4	0.0494
5	0.1270
6	0.2032
7	0.2696
8	0.3261
9	0.3742
10	0.4154
11	0.4511
12	0.4822

The above test should be performed at each exposure level. Over all exposure levels, if only one outlier is detected, it is recommended that that datum be discarded and the bias and variance analyses be performed on the remaining $n-1$ data. If more than one outlier is detected, the remaining analyses should be performed on all n data. The latter situation calls for analyzing all data as submitted on the assumption that the outliers may be due to lack of control of the process--a processor responsibility.

The critical values for the proposed test are at the 5% significance level for normally distributed measurements. Hence, the test is only an approximation for exposure levels, where the D_{ij} are not normally distributed.

After the test for outliers has been completed, the next step would be to estimate and test bias parameters. For these computations the procedure is to assume that

$$\bar{D}_i = \alpha + \beta E + \epsilon_{E_i} ,$$

and to estimate α and β with the weighted least squares estimates a and b given in Equations (B-23,B-24) of Section 4. The variances of these estimates and tests of the hypotheses $H_0^1: \alpha = 0$ and $H_0^2: \beta = 1$ are computed as shown in Equations (B-25-B-28) of Section 4. If H_0^1 or H_0^2 is rejected, then evidence of bias has been obtained.

When bias in a process is detected, then the processor should be notified, and, under certain circumstances, supplied with a bias correction formula. Let

$$\begin{aligned} a' &= a \text{ if } H_0^2 \text{ is rejected,} \\ &= 0 \text{ if } H_0^2 \text{ is not rejected,} \end{aligned}$$

and

$$\begin{aligned} b' &= b \text{ if } H_0^1 \text{ is rejected,} \\ &= 0 \text{ if } H_0^1 \text{ is not rejected.} \end{aligned}$$

The bias correction formula for future measurements with the process is

$$D_c = \frac{D - a'}{b'} , \quad (B-40)$$

This simple correction should help to remove much of the bias found in film badge dosimetry measurement processes. For example, some of the measurements from the process used to illustrate extreme bias in Figure B-5, Section 4, were corrected using the above formula. One measurement was chosen at random from each exposure level, corrected and plotted in Figure B-6. The open circles are the original measurements and the closed circles are the corrected measurements. Considerable improvement is noted.

FIGURE B-6. *Uncorrected and Corrected Sample Data for Process with Lowest "b" for the Photon-Intermediate Energy Radiation Category*

It was mentioned above that bias correction formulas would be allowed under certain circumstances. This restriction is necessary since the bias corrections can change the process variances, thus creating a process with variances too large to pass the test described later in this section. If a process has a bias estimate $b > 1$, then use of the correction formula would reduce σ_E^2 ; but if $b < 1$, then use of the correction formula would increase σ_E^2 . In either case, data should be

"corrected" prior to applying the variance test. Actually, it is not necessary to correct all data, but merely to multiply all S_i^2 's by $(1/b)^2$.

The derivation of the variance test was based on a desire to create a test that would be effective over a range of exposure levels for many processes. This consideration led to the choice of $\sigma_E^2 = \kappa E^2$ for a variance-exposure level relationship for ^{60}Co , X-ray (Radium and X-ray mixture) and fast neutron radiation types as explained in Section 4. Also, in Section 4, $\sigma_E^2 = \kappa E$ was chosen for a variance-exposure level relationship for all other radiation types. These relationships will be used to specify tests of hypotheses of variance magnitudes. That is, from the data submitted to the laboratory, m tests of $H_0: \sigma_{E_i}^2 \leq \kappa E_i^\mu$ ($\mu = 1$ or 2), $i = 1, 2, \dots, m$, will be performed, and approval of a process will depend on whether or not all of these hypotheses are accepted.

The values for κ were computed from the Industry Study data for groups of preselected technically proficient processors. The selection of these groups of processors was based on a consideration of their facilities and processing techniques, and did not involve consideration of the estimates of the variances for their processes.

For the group of processors selected, it was desirable to choose a method of computing κ that would tend to allow a high probability of some of the processors passing a subsequent test. Roughly, the idea was to let the selected group of processors (or, rather, processes) establish the magnitude of the variances allowable in the industry. Having done this, all other processes would be more likely or less likely to pass the variance test depending on whether their variances were less than or greater than the variances of the selected group.

The variance test for a process is to compare S_i^2 with K_i ,
 $i = 1, 2, \dots, m$,

where

$$K_i = \frac{\kappa E_i^\mu \chi_{\alpha; n_i-1}^2}{n_i-1}, \quad (B-41)$$

and

$\chi_{\alpha; n_i-1}^2$ = tabled chi-square value;

and to declare that the test has been passed only if $S_i^2 \leq K_i$ for all i . Assuming that the D_{ij} are normally distributed measurements with variance κE_i^μ , the probability that $S_i^2 \leq K_i$ is

$$P(S_i^2 \leq K_i) = \alpha. \quad (B-42)$$

Since S_i^2 and $S_{i'}^2$ are independent for $i \neq i'$, the probability that $S_i^2 \leq K_i$ for all i is

$$\prod_{i=1}^m P(S_i^2 \leq K_i) = \alpha^m. \quad (B-43)$$

This probability should be fairly high; hence, set $\alpha^m = 0.85$.

For the Industry Study data from our selected group of processors, there is a set of variance estimates available for each process. Let the observed values of these estimates be denoted S_{i1}^2 , $i = 1, 2, \dots, m$, for each of the five processes. Let the corresponding estimates for a subsequent test period at the same exposure levels be denoted by S_{i2}^2 . Fixing attention on one exposure level of one process, and still assuming normally distributed measurements,

$$\begin{aligned}
P\left(\frac{S_{i2}^2}{S_{i1}^2} \leq F_{\alpha; n_2-1, n_1-1}\right) & \quad (B-44) \\
&= \int_0^\infty P\left(\frac{S_{i2}^2}{S_{i1}^2} \leq F \mid S_{i1}^2 = s_{i1}^2\right) dG_{S_{i1}^2}(s_{i1}^2) \\
&= \int_0^\infty P\left(\frac{S_{i2}^2}{s_{i1}^2} \leq F \mid S_{i1}^2 = s_{i1}^2\right) dG_{S_{i1}^2}(s_{i1}^2) \\
&= P(S_{i2}^2 \leq s_{i1}^2 F) = \alpha;
\end{aligned}$$

where

$F_{\alpha; n_2-1, n_1-1}$ = tabled "F" value,

n_1 = first sample size,

n_2 = second sample size,

$P(\cdot | \cdot)$ denotes conditional probability function, and

$G_{S_{i1}^2}(s_{i1}^2)$ denotes the probability distribution function of S_{i1}^2 .

Extending our attention to all exposure levels of one process we have the probability that $S_{i2}^2 \leq s_{i1}^2 F_{\alpha; n_2-1, n_1-1}$, $i = 1, 2, \dots, m$, equal to α^m :

$$\prod_{i=1}^m P(S_{i2}^2 \leq s_{i1}^2 F_{\alpha; n_2-1, n_1-1}) = \alpha^m \quad (B-45)$$

Now, if we add a subscript "2" in Equation (B-42) and set Equation (B-42) equal to Equation (B-44), we have

$$s_{i1}^2 F = K_{i2} = \frac{\kappa E_{i2}^{\mu} \alpha^2; n_{i2}-1}{n_{i2}-1},$$

or

$$F = \frac{\kappa E_{i2}^{\mu} \alpha^2; n_{i2}-1}{s_{i1}^2 (n_{i2}-1)} \quad (B-46)$$

Suppose that we let $n_{i2} = 4$ for $i = 1, 2, \dots, m$, $\alpha = (0.85)^{1/m}$ and choose a value for κ . For each i , substitution in Equation (B-46) gives a different value of F , depending upon the values of E_{i2} and s_{i1}^2 . Let F_i denote these different values of F . Using Equations (B-44, B-45) and tables associated with the "F" distribution, we can compute

$$P(S_{i2}^2 \leq s_{i1}^2 F_i), \quad i = 1, 2, \dots, m, \quad (B-47)$$

and

$$\prod_{i=1}^m P(S_{i2}^2 \leq s_{i1}^2 F_i) \quad . \quad (B-48)$$

By trial and error we can determine a κ such that

$$\prod_{i=1}^m P(S_{i2}^2 \leq s_{i1}^2 F_i) = \alpha^m = 0.85 \quad . \quad (B-49)$$

One should be careful of the interpretation of the probability statement expressed by Equation (B-49). The meaning of this probability statement is that if pairs of sets of data are taken as in the Industry Study and as outlined for the test set above, the first set used to determine κ and the second set used for the variance test, and this process repeated many times; then the frequency with which the variance test is passed will be approximately 85/100. The probability statement does not mean that having fixed a κ with one set of data, the frequency of subsequent tests passed using that κ will be 85/100.

The κ derivation given above was for a single process, but we must consider five processes in our selected group. Each of these give rise to a different value of κ ; whereas, we wish to establish a single κ for the whole industry. Choosing the next to smallest κ leads to the following statement: the probability that one or more of the five selected processes will pass a subsequent variance test is at least 0.835. Proof

of this lies in the fact that the statement "one or more of the processes pass the test using the second smallest κ " is implied by the statement "four or more of the processes pass tests using their respective κ 's." The probability of the event described by the later statement is $(0.85)^5 + (4)^5(0.85)^4(0.15) = 0.835$; so the probability of the event described by the first statement is at least 0.835. Again, this probability statement is interpreted as the frequency of one or more passed tests in repetitions of the whole procedure.

The κ values for all radiation types used in the study are given in Table B-IX. The criterion for radium gamma radiation is that $\sigma_E^2 \leq 2.3E$ in the exposure range $60 \text{ mrem} \leq E \leq 1000 \text{ mrem}$; for ^{60}Co , $\sigma_E^2 \leq 0.0008E^2$ in the exposure range $40,000 \text{ mrem} \leq E \leq 600,000 \text{ mrem}$; etc. Tests against these criteria will be performed by the Laboratory.

TABLE B-IX. Experimental Results, κ Values for Variance Tests

Radiation Type	Exposure Range, mrem	κ
Ra	60 - 1000	2.3
^{60}Co	40,000 - 600,000	0.0008
170 keV X-ray	60 - 1000	7.1
100 keV X-ray	60 - 1000	8.5
17 keV X-ray	60 - 240	0.6
U	120 - 500	1.2
γ (Ra and U mix.)	120 - 500	2.3
β (Ra and U mix.)	120 - 500	3.3
γ (Ra and 17 keV X-ray)	120 - 500	2.3
X-ray (Ra and 17 keV X-ray mix.)	120 - 500	0.005
γ + X-ray (Ra and 17 keV X-ray mix.)	240 - 1000	2.9
Thermal Neutrons	60 - 400	0.9
Fast Neutrons	200 - 800	0.03

The foregoing procedure for computing κ was followed for all radiation types. In certain instances, the κ arrived at is not the value shown in Table B-IX. The value of κ for gamma + X-ray (Radium and 17 keV X-ray mixture) was taken to be the sum of the κ 's for Radium gamma and 17 keV X-ray types.

For gamma (Radium and 17 keV X-ray mixture), gamma (Radium and U mixture) and X-ray (Radium and 17 keV X-ray mixture), the κ values were smaller than the corresponding values for non-mixtures. In these cases, κ was set equal to the value derived for the nonmixed radiation type. The value of κ for fast neutrons was also modified for use as a variance performance criteria based on a professional judgement as discussed in the main text of this report.

The $\chi^2_{\alpha; n_i-1}$ values used in computing the critical values K_i depend on the number of levels m chosen for the variance test and the number of exposures n_i at each exposure level. These values are given in Table B-X.

TABLE B-X. χ^2 Values for the Variance Test

	(m)								
	2	3	4	5	6	7	8	9	10
2	3.10	3.73	4.20	4.60	4.90	5.16	5.40	5.60	5.80
3	5.10	5.86	6.40	6.86	7.20	7.50	7.80	8.00	8.26
4	6.80	7.68	8.32	8.80	9.19	9.54	9.80	10.07	10.33
5	8.40	9.35	10.10	10.60	10.95	11.35	11.70	11.92	12.20
6	9.85	10.90	11.65	12.20	12.65	13.05	13.40	13.70	13.95
(n_i) 7	11.35	12.40	13.20	13.70	14.25	14.68	15.00	15.25	15.55
8	12.77	13.90	14.71	15.33	15.80	16.25	16.62	16.90	17.16
9	14.12	15.33	16.14	16.82	17.30	17.75	18.28	18.46	18.83
10	15.50	16.75	17.59	18.25	18.80	19.27	19.70	19.98	20.38
11	16.83	18.12	19.00	19.73	20.12	20.38	21.15	21.50	21.85
12	18.17	19.47	20.40	21.15	21.65	22.21	22.63	22.97	23.33

This table was constructed to give tests with equal significance levels at m exposure levels, n_i exposures at each level, and to give a significance level $1 - \alpha^m = 0.15$ for the overall test.

The properties of the variance test are that it allows for an increasing variance-exposure level relationship; the probability of rejecting $H_0: \sigma^2 = \kappa E^\mu$ ($\mu = 1$ or $\mu = 2$), when the hypothesis is true, is constant at all m exposure levels E_i ; and the probability of accepting H_0 , when it is true, at all m

exposure levels (i.e. passing the test) is 0.85. The power of the test (probability of failing when κ is greater than shown in Table B-X) is shown for hypothetical examples in the first part of this report.

The data collection procedure prescribed at the beginning of this Section should be followed in the early stages of operation of the Laboratory. If the attempt to remove biases from the measurements is successful, then bias tests may no longer always be necessary and alternate data collection procedures may prove to be useful. For radiation types where the variance hypothesis is $H_0: \sigma^2 = \kappa E$, the sum of p measurements made at different exposure levels E_i will, under the null hypothesis, have the same variance as a single measurement at exposure level $E = \sum_{i=1}^p E_i$. Using this fact, it then becomes possible to test $H_0: \sigma^2 = \kappa E$ at exposure level E_i by obtaining n_i sets of measurements ($n_i \leq 2$) containing $p_1, p_2, \dots, p_{n_i}$ measurements at exposure levels

$$E_{ijk}, j = 1, 2, \dots, n_i \text{ and } k = 1, 2, \dots, p_j,$$

where

$$\sum_{k=1}^{p_1} E_{i1k} = \sum_{k=1}^{p_2} E_{i2k} = \dots = \sum_{k=1}^{p_{n_i}} E_{in_i k} = E_i \quad . \quad (B-50)$$

The computation of the sample variance S_i^2 is then made using the sums of the measurements for each of the n sets. If those measurements are denoted D_{ijk} , then in Equation (B-41)

$$D_{ij} = \sum_{k=1}^{p_j} D_{ijk} \quad . \quad (B-51)$$

This procedure constitutes additional freedom in data collection for variance tests. It provided the reason for choosing $\mu = 1$ when we considered the class of variance-exposure level relationships specified by $\sigma^2 = \kappa E^\mu$, $0 < \mu < 2$ in Section 4.

A numerical example is given in Section 6.

In summary, this Section contains prescribed data collection procedures; a rounding discussion; recommended outlier, bias and variance tests; a bias correction discussion; and the derivation of the variance criteria constants.

6. RECOMMENDED LABORATORY DECISION PROCEDURES

In Section 5, there were comments on the actions that a Film Dosimetry Calibrations Laboratory should take as the consequence of various test results. The sequence of tests, their results, and the ensuing actions is referred to here as the Recommended Laboratory Decision Procedure. This Procedure is diagramed in Figure B-7. Actions are contained in rectangles, and results are contained in circles.

In scientific investigations, data are often screened for outliers by trying to find some experimental defects that explain apparent discrepancies. If explanations are found, then the discrepant data are discarded or corrected. Unfortunately, the Film Dosimetry Calibration Laboratory will not be in a position to rapidly check possible physical causes of outliers. Hence, a statistical test for outliers should be conducted at each exposure level.

When the purpose of a data analysis is to draw inferences from a well controlled experiment, all outliers are removed. But the purpose of the data analysis to be performed by the Laboratory is not only to draw inferences about a film badge dosimetry measurement process, but also to judge how well that process is controlled. Since some outliers may be due

FIGURE B-7. Action-Result Chart for
Laboratory Decision Procedure

to poor control, removal of all outliers would tend to thwart part of the purpose of the analysis. It is recommended, therefore, that when one outlier is detected it should be discarded, and when more than one is detected, all data, including outliers, should be analyzed. Allowing outliers to remain in the data will increase the variance estimates, thus making it less likely that the process will pass the variance test.

Occasionally, processes will be approved even though there are outliers present. In such cases, final notification to the processor should include identification of the outliers so that he can properly judge whether to use any allowable bias correction. If he judges the outliers to be atypical, then he should not use a bias correction but, instead, submit a new set of badges for retesting.

The purpose of the bias tests is twofold: to obtain evidence of bias when it is present, and to provide estimates of the bias parameters for use in the bias correction formula. When no bias is detected, it may be due to excessive variance in the measurement process and insufficient data. Nevertheless, since the Laboratory has no evidence of bias, it should conduct the variance test. When bias is detected, evidence is in hand and the bias correction is likely to be effective. However, multiplicative bias corrections alter the process variance-exposure level relationship, and the variance test should be conducted on "corrected data". That is, the variance test will be a test of the corrected process variance.

The Laboratory should disapprove processes that fail the variance test. In notifying the processor of the disapproval, the results of the bias tests should be reported. Even though a processor has not gained approval for his process, he may profit from information on detected bias by seeking out the causes of the bias or by making the bias corrections.

A process passing the variance test and having no excessive bias should be given an unqualified approval. Such a process has supplied evidence of control that meets the criteria established in Section 5. A biased process passing the variance test should not be given an unqualified approval. Instead, the processor should be notified that his process is approved providing that the bias correction formula is used. If the processor chooses to attempt to remove the bias causes rather than use the correction formula, he should then be required to submit a new set of badges for retesting.

Radium Gamma Radiation Exposures

Dose Levels:

$$E_1 = 100 \text{ mrem} \qquad E_2 = 425 \text{ mrem} \qquad E_3 = 650 \text{ mrem}$$

Number of Dosimeters:

$$n_1 = 3 \qquad n_2 = 3 \qquad n_3 = 5$$

The data reported (mrem) and the basic computations are

<u>j</u>	<u>D_{1j}</u>	<u>D_{2j}</u>	<u>D_{3j}</u>
1	165	770	962
2	174	744	1000
3	170	110	1025
4			993
5			980

Average Dose:

$$\bar{D}_1 = 169.7 \qquad \bar{D}_2 = 541.3 \qquad \bar{D}_3 = 992.0$$

Variance:

$$S_1^2 = 20.33 \qquad S_2^2 = 139,705.33 \qquad S_3^2 = 549.5$$

Outlier Tests:

Omit D_{11} , D_{23} and D_{33} as being most deviant from their respective means. Compute:

$$S_1'^2 = 8.00 \quad S_2'^2 = 338.00 \quad S_3'^2 = 278.92$$

$$S_1'^2/S_1'^2 = 0.3935 \quad S_2'^2/S_2'^2 = 0.0024 \quad S_3'^2/S_3'^2 = 0.5076$$

Entering table B-VIII:

$$S_1'^2/S_1'^2 > 0.0027 \quad S_2'^2/S_2'^2 < 0.0027 \quad S_3'^2/S_3'^2 > 0.1270$$

Hence, D_{23} is rejected as an outlier.

Let $n_2 = 2$, $S_2^2 = S_2'^2 = 338.00$ and compute $\bar{D}_2 = (770 + 744)/2 = 757$

Bias Estimates and Tests:

$$w_1 = \frac{n_1}{S_1^2} = \frac{3}{20.33} = 0.148, \quad w_2 = 0.006, \quad w_3 = 0.009;$$

$$\sum w_i = 0.148 + 0.006 + 0.009 = 0.163,$$

$$\sum w_i \bar{D}_i = (0.148)(169.7) + \dots + (0.009)(992.0) = 38.59,$$

$$\sum w_i E_i = (0.148)(100) + \dots + (0.009)(650) = 23.20,$$

$$\begin{aligned} \sum w_i \bar{D}_i E_i &= (0.148)(169.7)(100) + \dots + (0.009)(992.0)(650) \\ &= 10245.11, \end{aligned}$$

$$\sum w_i E_i^2 = (0.148)(100)^2 + \dots + (0.009)(650)^2 = 6366.25,$$

$$\begin{aligned} b &= \frac{\sum w_i \bar{D}_i E_i - [(\sum w_i \bar{D}_i)(\sum w_i E_i)/\sum w_i]}{\sum w_i E_i^2 - [(\sum w_i E_i)^2/\sum w_i]} \\ &= \frac{10245.11 - [(38.59)(23.20)/0.163]}{6366.25 - [(23.20)^2/0.163]} = 1.55, \end{aligned}$$

$$\begin{aligned} a &= (\sum w_i \bar{D}_i / \sum w_i) - b(\sum w_i E_i / \sum w_i) \\ &= (38.59/0.163) - 1.55(23.20/0.163) = 16.11, \end{aligned}$$

$$\begin{aligned} \hat{\sigma}_b^2 &= \left\{ \sum w_i E_i^2 - [(\sum w_i E_i)^2 / \sum w_i] \right\}^{-1} \\ &= \{6366.25 - [(23.20)^2 / 0.163]\}^{-1} = 0.00032, \end{aligned}$$

$$\begin{aligned}\sigma_a^2 &= \left(\sum w_i E_i^2 / \sum w_i \right) \sigma_b^2 = (6366.25/0.163)(0.00032) \\ &= 12.50; \\ \frac{|b-1|}{\sigma_b} &= 30.76 > 1.96; \\ \frac{|a|}{\hat{\sigma}_a} &= 4.56 > 1.96;\end{aligned}$$

Hence, conclude that $\beta \neq 1$ and $\alpha \neq 0$.

Bias Criteria:

Since $\frac{D(b'-1) + a'}{D-a'} > 0.1$, bias correction is required.

Dose of 100 mrem:

$$\frac{100(1.55-1) + 16.11}{100-16.11} = 0.84.$$

Dose of 425 mrem:

$$\frac{425(1.55-1) + 16.11}{425-16.11} = 0.61.$$

Dose of 650 mrem:

$$\frac{650(1.55-1) + 16.11}{650-16.11} = 0.59.$$

All data points have bias in excess of 10%; hence, a bias correction is necessary.

Bias Correction:

$$D_c = \frac{D-a'}{b'} = \frac{D-16.11}{1.55}$$

Variance Estimates Corrected for Bias:

$$\left(\frac{1}{b}\right)^2 S_1^2 = \frac{1}{(1.55)^2} (20.33) = 8.46;$$

$$\left(\frac{1}{b}\right)^2 S_2^2 = 140.69;$$

$$\left(\frac{1}{b}\right)^2 S_3^2 = 228.72.$$

Variance Test:

For Radium gamma radiation type in Table B-IX find $\kappa = 2.3$.

In Table B-X, for $m = 3$ levels of exposure and $n_1 = 3$, $n_2 = 2$, $n_3 = 5$; find $\chi_1^2 = 5.86$, $\chi_2^2 = 3.73$ and $\chi_3^2 = 9.35$.

Compute:

$$K_1 = \frac{\kappa^2 E_1 \chi_1^2}{n_1 - 1} = \frac{(2.3)(100)(5.86)}{3-1} = 673.90;$$

$$K_2 = 3646.08;$$

$$K_3 = 3494.56.$$

Since $\frac{1}{b^2} S_i^2 < K_i$ ($i = 1, 2, 3$), this process passes the variance test and receives Laboratory approval, providing that the bias correction, $\frac{D - 16.11}{1.55}$, is used.

The Recommended Laboratory Decision Procedure described in this section covers the actions that should be taken from the results of the recommended statistical tests. It is meant to be an automatic procedure that can be routinely applied by the Laboratory. However, it is not meant to inhibit intelligent data analysis and use of the information gained. The judgement of the Laboratory Director should play a part in deciding when temporary deviations from the above procedure may be beneficial.

7. SURVEY OF PROCESSORS CURRENT OPERATING PRACTICES

In concurrence with the test irradiation program, a questionnaire was sent to each participant to determine some of the operational methods and equipment used in providing film services. This section summarizes the results of this survey.

As a part of the test irradiation program, a questionnaire was sent to each participant to determine some of the operation methods and equipment used in providing a film dosimeter service, and to determine if some operational methods or equipment lead to similar performance characteristics among processors. The data is currently being analyzed to determine if any such relationships exist. If significant correlations are discovered, they will be reported separately. The following Tables summarize the reported information.

The duPont packet with the sensitive dosimeter film designated as 519, is used by 50% of the processors. The choice of insensitive dosimeter film is nearly equally divided between duPont 834 and duPont 1290. Only four of the 31 processors responding to the questionnaire indicated the use of the Kodak Personnel Monitoring Films in their film dosimeters. Table B-XI summarizes the use of various film types by processors.

TABLE B-XI. Beta-Gamma Film Packets

<u>Type of Packet</u>	<u>Number of Users</u>
duPont 544 (555 + 834)	6
duPont 556 (519 + 834)	8
duPont 558 (519 + 1290)	8
duPont SX-249 (555 + 1290)	5
Kodak Type 2	2
Kodak Type 3	2

In fast neutron dosimeters, NTA film is used exclusively. Only 40% of the processors use a special dosimeter for fast neutron dosimeters. The remainder generally add a piece of NTA film to the conventional beta-gamma dosimeter. Table B-XII summarizes the use of fast neutron dosimeters.

TABLE B-XII. *Dosimeters for Fast Neutrons*

<u>Dosimeter Used</u>	<u>Number of Users</u>
Special Dosimeter	9
Beta-Gamma Dosimeter (with NTA film)	14

Thermal neutrons are detected with either beta-gamma type film or nuclear emulsion track film. Processors do not use a special dosimeter for thermal neutron dosimetry, but they do use their regular beta-gamma dosimeter or their fast neutron dosimeter with special features and detectors added to attain a thermal neutron response. Table B-XIII summarizes the detectors and dosimeters used.

TABLE B-XIII. *Thermal Neutron Dosimetry*

<u>Dosimeter Used</u>	<u>Thermal Neutron Detector Element</u>	
	<u>Beta-Gamma Film</u> <u>No. of Users</u>	<u>NTA Film</u> <u>No. of Users</u>
Beta-Gamma Dosimeter	4	4
Fast Neutron Dosimeter	1	4

The radionuclides commonly used for calibration sources are Radium-226, Cobalt-60, and Cesium-137. Some of the processors use more than one radionuclide for calibrations, depending upon both the dose range and the expected energy range to be monitored. Cobalt-60 was the most commonly used radionuclide source. Table XIV summarizes the number of users of each of the commonly used sources.

TABLE B-XIV. *Radionuclide Calibration Sources*

<u>Radionuclide</u>	<u>Number of Users</u>
Radium-226	12
Cobalt-60	20
Cesium-137	13
Other	4

For beta radiation calibrations, natural uranium and ^{90}Sr beta sources are commonly used. The uranium sources are used as wide angle sources where the dosimeters to be calibrated are placed essentially on the surface of the uranium. For this exposure geometry, the beta particles hit the film emulsion over a wide angle of incidence. For ^{90}Sr calibration a point source is commonly used and the dosimeters are calibrated at some distance from the source. This geometry of exposure results in more nearly parallel beta particles penetrating the film emulsion at a near normal angle. This calibration procedure more nearly approximates field exposure conditions. It results in somewhat less film density per unit of dose (measured in air at a point of interest) than the uranium surface calibration provides. Film dosimeters calibrated on a uranium slab and used for typical beta field dosimetry will tend to underestimate the dose actually received. Two-thirds of all processors are currently using surface uranium exposures for beta radiations calibrations. Table B-XV summarizes beta radiation sources.

TABLE B-XV. *Beta Radiation Calibration Sources*

<u>Radiation Source</u>	<u>Number of Users</u>
Natural Uranium	22
^{90}Sr	8
Other	3

Processors are about equally divided in the use of filtered X-rays and unfiltered X-rays for intermediate and low energy X-ray calibrations. Only 10% of the processors use fluorescent X-rays for calibrations in the 17 keV energy range. Table B-XVI summarizes the types of X-ray radiation sources used.

TABLE B-XVI. *X-ray Calibration Sources*

<u>Radiation Source</u>	<u>Number of Users</u>
Unfiltered X-rays	14
Filtered X-rays	16
17 keV Fluorescent X-rays	3

For thermal neutron calibration, 70% of the processors use a radionuclide neutron source plus moderation. Only a single processor utilizes a neutron generator machine for this calibration. It was rather surprising to find that only a few processors used a photon calibration with a correlation factor for thermal neutron calibration. The sources used are summarized in Table B-XVII.

TABLE B-XVII. *Thermal Neutron Calibration Sources*

<u>Radiation Source</u>	<u>Number of Users</u>
Radioactive source plus moderation	10
Neutron generator plus moderation	1
Other	3

About 60% of the fast neutron calibrations are performed with PuBe neutron sources (4.5 MeV). Some groups with special neutron dosimetry problems use a PuF₄ source to attain lower energy neutrons (1.4 MeV) for calibration. Table B-XVIII summarizes the fast neutron calibration sources in general use.

TABLE B-XVIII. *Fast Neutron Calibration Sources*

<u>Radiation Source</u>	<u>Number of Users</u>
PuBe	16
PuF ₄	3
Accelerator-Reaction	1
Other	6

It was of interest to note the various general shapes of the calibration curve used for relating film density to dose for gamma, X-ray, and beta radiations. One-third of the processors use a linear relationship to relate film density to radiation dose. Nearly one-half of the processors indicated that they use some "other" density-dose relationship than listed in Table B-XIX. This "other" entry usually refers to the establishment of the best fit curve through the data by visual methods.

TABLE B-XIX. *Types of Calibration Curves*

<u>Type of Curve</u>	<u>Number of Users</u>		
	<u>Gamma</u>	<u>X-ray</u>	<u>Beta</u>
Linear	11	6	9
Quadratic	1	1	1
Cubic	1	1	1
Exponential	3	3	3
Other	15	10	12

In making radiation exposures for calibration purposes, two techniques of attaining different radiation doses are commonly used. In the first technique, one maintains a fixed distance between the radiation source and the dosimeter. In well designed facilities, this assures constant scatter factors, constant energy spectra, and constant electronic equilibrium conditions for all dosimeter exposures. This method should yield equal dosimeter filter ratios for all radiation doses. In the test irradiation program conducted as a part of this study, this technique was used. The second exposure technique is to expose a set of dosimeters for a constant time at various distances from the radiation source. Under these conditions the scatter factors, energy spectra, and electronic equilibrium status may change from one dosimeter location to another. In well controlled and properly designed facilities, these factors can be reduced to values that do not significantly effect the dosimeter filter ratios.

Most processors favored the use of the fixed distance calibration technique, but many found it appropriate to use both techniques. Table B-XX summarizes the dosimeter calibration exposure techniques used for gamma, X-ray, beta and neutron radiations.

TABLE B-XX. *Dosimeter Calibration Exposure Techniques*

Technique	Number of Users			
	Gamma	X-ray	Beta	Neutrons
Fixed distance, variable time	14	10	20	9
Fixed time, variable distance	5	2	0	1
Both	12	9	5	5

The accuracy of positioning dosimeters for calibration exposures merits careful consideration in any dosimeter calibration program. As distances between radiation sources and the dosimeters decrease, small errors in positioning can lead to significant errors in the delivered dose. Table B-XXI lists the range of the maximum radiation source to dosimeter calibration distances reported by the processors. Calibrations performed at distances of 10 to 15 cm require extreme care in dosimeter positioning if calibration exposures are to be reproducible to 5% or better.

TABLE B-XXI. *Range of Maximum Source-Dosimeter Calibration Distances*

<u>Radiation Type</u>	<u>Range of Maximum Distance in cm</u>
Gamma	15 to 610
Beta	0 to 50
X-ray	8.9 to 610

APPENDIX C
PROPOSED FILM DOSIMETRY CALIBRATION LABORATORY

APPENDIX C

PROPOSED FILM DOSIMETRY CALIBRATION LABORATORY1. INTRODUCTION

To conduct a film dosimeter evaluation program and to provide a calibration service to film dosimeter processors, a Film Dosimetry Calibration Laboratory would be required. This Laboratory should be designed to provide known radiation exposures for both the evaluation and calibration program with accuracies sufficient to not significantly influence the performance evaluation. The design of the facility and the basic equipment requirements for a typical Laboratory are described in this section. Also some suggested operating procedures and schedules for the dosimeter evaluation program are included. While the equipment requirements may be altered in kind, it is important that the total equipment complement of the Laboratory remains similar to that described. To lessen the capability of the Laboratory would lessen the value of the evaluation and calibration programs.

The operational methods recommended for the Laboratory should be considered as suggested approaches and are expected to be modified as necessary to meet new or changing needs of the Laboratory. In this section, the terminology "Film Dosimetry Calibration Laboratory" is used interchangeably with the word "Laboratory" and is intended to refer to a facility that would provide both a Film Dosimeter Processor Evaluation Program and a Film Dosimeter Calibration Program. If only the later function is implemented, appropriate modifications to the Laboratory equipment requirements should, of course, be made. These changes appear to be minor and the cost and equipment requirements for establishment for the Laboratory for this purpose alone would result in little change in the Laboratory described.

2. SCOPE OF LABORATORY FUNCTIONS

The Film Dosimetry Calibration Laboratory should provide service to all film dosimeter processors, to their customers and to regulatory agencies in four major areas of activity:

- Verify good film dosimeter performance
- Identify processors meeting performance criteria
- Provide routine and special dosimeter calibrations
- Promote good personnel dosimetry

Verify Good Film Dosimeter Performance

A primary objective of the Film Dosimetry Calibration Laboratory is the verification of adequate performance by film dosimeter processors. This objective can be accomplished by a test dosimeter irradiation and evaluation program composed of the four major areas of activity:

- Provide test dosimeter irradiation exposures
- Analyze test exposure data
- Compare observed performance and performance criteria
- Schedule continuing test dosimeter irradiations

The Film Dosimetry Calibration Laboratory should provide test dosimeter irradiation exposures to film dosimeters submitted to it by film dosimeter processors. The exposures should be divided into nine radiation categories or sub-categories based on radiation type, radiation energy and dose equivalent range. Each processor should be tested in all radiation categories in which a service is provided, whether routine or non-routine, but not in those radiation categories in which a service is not provided.

The test dosimeter irradiation exposure data should be analyzed to determine if the performance criteria were met. The bias and variance observed should be determined. An attempt to eliminate all bias in excess of 10% (expressed as a percent of dose) should be made. It appears that the

bias can be eliminated by a careful re-examination and re-calibration of standard radiation sources and radiation exposure calibrations or by the use of film dosimeter calibration exposures provided by the Laboratory. Some bias may arise because of different methods of calibration, for example, using a backscatter exposure geometry with some calibrations or not using a backscatter. If all attempts to locate and eliminate bias in excess of 10% fail, a bias correction factor can be provided by the Laboratory to each processor requiring one and this factor should be used by the processor for all evaluations in that radiation category.

The variances observed should be compared with the variance specification part of the performance criteria. The observed variance needs to be within the limits prescribed by the specification for each radiation category and dose level.

Identify Processors Meeting Performance Criteria

All processors demonstrating their ability to meet the adopted performance criteria should be identified as having met the performance criteria. The regulatory organization concerned should be promptly informed of all processors meeting the established performance criteria. No additional release of the performance identification or the status of a processor should be contemplated by the Laboratory. The meeting of the performance criteria should increase confidence by customers, potential customers or the regulatory organizations.

For those personnel dosimetry services that enter the field of thermoluminescent or radiophotoluminescent dosimetry on a routine basis, the Laboratory would certify that dosimeters of this type meet the performance criteria which have been established for the film dosimeter processors.

It is reasonable to require that those offering thermo-luminescence or other systems for personnel dosimetry provide dosimeters which at least meet the minimum standards established for the film dosimeters. To this end, the Laboratory should provide verification of adequate performance for these new dosimeters.

Routine and Special Dosimeter Calibrations

The Film Dosimetry Calibration Laboratory should assist the film dosimeter processors by providing both routine and special dosimeter calibrations. The routine calibration service would provide calibrated film dosimeter irradiations for those processors desiring to purchase this service. In practice, a processor would send the Laboratory film dosimeter and request their exposure to given doses of the desired radiations. After the exposures, the dosimeter would be returned to the processors where they would be used as calibration control films, one set being developed with each batch of unknown film. The calibration service could play a major role in eliminating bias. It would go far to assure the use of uniform standard radiation sources, uniform exposure conditions and well known calibration exposure controls. By using this service, a processor could eliminate his need to buy, maintain and calibrate radiation sources. The processors would also avoid the need to make calibration exposures within their facilities. This should result in decreased costs for a film dosimeter processor by eliminating the need to buy and maintain standard radiation sources and facilities suitable for making calibration exposures. Of course, the elimination of exposures to radiation sources could reduce film fogging that may arise from inadequately shielded film stored by a processor prior to its use.

A processor continuing to do this routine calibration exposures could purchase from the Laboratory, non-routine

exposures to radiation sources or to dose levels not easily obtained within his facilities. This might be especially desired for some monoenergetic irradiations for special source irradiations, or for the high doses required for accident dosimetry capability.

In all of these calibration service activities, the Laboratory would guard against providing functions properly obtained from the U.S. Bureau of Standards. For example, the Laboratory would not calibrate or certify radiation sources or radiation dose measurement instruments.

Promote Good Performance

The Laboratory procedures, policies and programs should be designed to promote good performance by film dosimeter processors. As new needs are discovered and requests for expanded or additional services become known, those programs which will promote good performance should be adopted. The activities of the Laboratory should be designed to help all dosimeter processors and to meet their needs at every opportunity.

All activities of the Laboratory should be reported in a summary form on an annual basis and each processor should receive a copy. This summary should not identify the status of the observed performance of any processor. When new developments are made or when particularly difficult problems are solved, the results should be documented and distributed to all who may have an interest. Particularly, all new technology used by the Laboratory should be promptly published.

3. LABORATORY FACILITIES

Facilities required for the Film Dosimetry Calibration Laboratory consist of the land on which the Laboratory building is placed and the building itself. The land and

building aspects of the Laboratory need to be closely integrated. There is a need to have a low scatter irradiation building so that calibration work may be completed with the required accuracy and there is also a need for low radiation at the external building walls. These conditions can be met by a relatively large building so that the inverse square law and moderate shielding in the outer walls will reduce the dose rate from exposed radiation sources and radiation generating machines to acceptable levels at the exterior of the building walls. The construction of a moderate size building on a large lot which can have rigidly controlled access so that the external environment at the building wall need not be reduced to non-control levels is preferred on a cost basis. In areas of high land cost, however, this alternative may not be the preferred one and a moderately large building with adequate external wall shielding may be required. In any case, the variation in the scatter at the positions of film dosimeter calibrations should not exceed the variations due to dosimeter positioning on the test irradiation jigs. The test irradiation program demonstrated that variations in dosimeter evaluations due to positioning errors can be held to 2%. Control of radiation variations to within 2% will help to assure that the Laboratory does not contribute significantly to any variances measured as a part of the performance evaluation.

Control of the scatter variations can be accomplished by two methods if it is not feasible to eliminate them by the facility design. First, if the total radiation dose including scattered radiation contributions is measured at each dosimeter location, then the actual dose to each dosimeter is known. Second, a rotating exposure jig can be designed so that each dosimeter spends the same portion of its total calibration time at each position about the source. In spite of these methods to minimize the effects of the scattered radiations,

errors may yet arise due to the difference in energy between the primary radiation and the scattered radiation. The large scatter free irradiation room is the preferred approach to conducting an accurate test irradiation program.

The Film Dosimetry Calibration Laboratory will require a building designed for radiation source handling and storage and for provision of two low scatter irradiation rooms in which dosimeters are to be exposed. Additionally a shielded administrative office area is required for the staff. Special features of the building will include a film dosimeter storage area of constant low background radiation and controlled temperature and humidity so that film dosimeters can be stored prior to and after exposure. In the design of the Laboratory building, flexibility in the use of all of its facilities should be provided. The required Laboratory facilities are:

- Irradiation rooms
- Radiation source storage vault
- Film dosimeter storage vault
- Administration offices.

Irradiation Rooms

Two irradiation rooms will be required. The larger of these rooms should be a low radiation scatter irradiation room with a minimum length, width and height of 30 feet each. This room will provide space for the gamma and X-ray exposures under low radiation scatter conditions. The radiation scatter contribution to the volume bound by the central 15 foot cube should be constant to within 2%. These conditions are required to assure that variances determined in the evaluation of performance are not due to the Evaluation Program itself. A good facility layout would place this room at one end of the Film Dosimetry Calibration Laboratory building with a shielding wall of about one foot of concrete between the irradiation

room and the rest of the building. The shielding wall is required to provide shielding for personnel and for other calibration exposures being conducted in other parts of the building. Dose rates in the administrative areas of the Laboratory should be less than 0.2 mrem/hr at all times during normal operation. A doorway with an appropriate interlock should be provided to prevent inadvertent entry into the irradiation room.

The second irradiation room may be smaller than the first, measuring about 20 feet on a side and with about a 12 foot ceiling. This room would be used for the beta, thermal and fast neutron and high dose equivalent exposure irradiations. It should have a suitable interlock to prevent inadvertent entry and should be shielded to assure that dose rates to the administrative areas are less than 0.2 mrem/hr.

Radiation Source Storage Vault

When not in actual use or housed in well shielded storage casks designed as part of a radiation exposure jig, all radiation sources should be stored in a fireproof, shielded storage vault. The storage vault should provide a labyrinth entrance and shielding equivalent to about two feet of concrete on all sides and the ceiling. A suitable vault entry interlock should be provided. Internal dimensions of about an 8 foot cube are desired. Continuous air samples should be drawn from the vault. The activity of the air sample is required to provide a constant knowledge of the contamination status of the vault and to provide prompt detection of any radiation source leakage. Experience has shown that an air sample system such as this is effective in radiation source leakage detection.

Film Dosimeter Storage Vault

A film dosimeter storage vault with a constant low radiation background should be provided. This vault is

necessary to provide a storage area for all film dosimeters while not actually being exposed at the Laboratory. The temperature and humidity in the vault should be controlled to provide film storage at the conditions recommended by the film manufacturing companies. An internal vault volume of about 100 ft³ should be provided. Shielding of lead, steel or concrete may be used. The vault should be located near the area of package delivery to the building. The conduct of the Laboratory test dosimeter irradiation program should not increase the dose rate within the vault by more than a factor of 2 to 5.

Administration Offices

Four administrative offices of about 200 ft² each are required. These offices provide space for the director, engineer, technician and secretary. The dose rates in the offices should not exceed 0.2 mrem/hr during the normal operation of the Laboratory. There are no other special requirements for the office design.

4. LABORATORY EQUIPMENT

The equipment requirements of a Film Dosimetry Calibration Laboratory can be classified into four general areas:

- Radiation Sources
- Radiation Dose Standardization Instrumentation
- Test Irradiation Dosimeter Exposure Jigs
- General Instrumentation

Radiation Sources

The Laboratory should be well equipped with radiation sources and radiation generating equipment to meet its objectives and the needs of its customers. The radionuclide sources, source strengths and the number of each type of radionuclide source required are shown in Table C-I.

TABLE C-I. Radionuclide Sources Required

<u>Radiation Source</u>	<u>Source Strength Curies</u>	<u>Number Required</u>	<u>Applications</u>
Radium	0.5	2	Photon Exposures
Radium	0.01	2	Photon Exposures
^{60}Co	5	1	Photon Exposures
^{60}Co	1	1	Photon Exposures
^{60}Co	0.2	2	Photon Exposures
^{137}Cs	1	1	Photon Exposures
^{192}Ir	1	1	Photon Exposures
^{90}Sr	0.003	2	Beta Exposures
^{90}Sr	0.0001	2	Beta Exposures
Uranium	(8 x 1 x 1/4 in. Slabs)	20	Beta Exposures
PuBe	(80 g Pu)	2	Neutron Exposures

The radium, cesium and iridium sources would be used for the test irradiation exposures of the gamma photon radiation categories (1-A, 4-A, 4-B) of the performance criteria. Test exposures would be made in the dose equivalent range from 40 to 1000 mrem. All photon exposures for radiation category 1-B would be made with ^{60}Co . The beta radiation exposures would normally be provided by exposing dosimeters to polished slabs of normal uranium in equilibrium with its daughters. Some special beta radiation exposures would require the ^{90}Sr beta radiation sources.

The PuBe neutron sources will be used for both thermal and fast neutron calibration. Calibration for intermediate energy neutrons should not be provided at this time because of the lack of a suitable personnel dosimeter for this neutron energy range. For the thermal neutron calibration, a graphite moderator sigma pile is the best way to provide the necessary neutron moderation. In the interest of economy, a paraffin or polyethylene moderator, measuring several feet on each side, may

be used to moderate the fast neutrons from a PuBe neutron source and provide the thermal neutron exposures. The fast neutron exposures will be made by using the PuBe neutron source in air under low scatter conditions.

In addition to the radiation sources listed in Table C-I, radiation generating machines as shown in Table C-II will be required.

TABLE C-II. Radiation Generating Machines

<u>Radiation Source</u>	<u>Radiation Type</u>	<u>Energy Range</u>
X-ray	X-ray	20 to 300 kVp
K-fluorescent	X-rays	8 to 100 keV

An X-ray generating machine with an output range from 20 to 300 kV is recommended for the X-ray test exposures. It would be convenient, but not mandatory, if two X-ray machines were available. One machine would have an output energy range from 10 to 50 kV and would be used primarily with the K-fluorescent X-ray sources; the other would provide an output energy range from 50 to 300 kV and would be used for the generation of radiation simulating that encountered in typical diagnostic and medical treatment X-ray exposures. This X-ray machine would also be used as an X-ray source for heavily filtered X-rays. Both X-ray machines should be mounted so that their beams could be directed to the geometric center of the large irradiation exposure room. The control center for the X-ray machine(s) should, of course, be located in a well shielded location. Both X-ray machines should be continuous duty and well stabilized.

A complete K-fluorescent X-ray source is required. Irradiation fields of at least 6 in. in diameter are required so that at least four test dosimeters can be exposed simultaneously. A K-fluorescent X-ray source similar to that described by Larson, Myers and Roesch⁽¹⁶⁾ would be appropriate.

The typical K-fluorescent radiation source would include the irradiators shown in Table C-III so that a wide range of monoenergetic energies could be attained.

TABLE C-III. *K-Fluorescent Radiation Sources*

<u>Radiator Material</u>	<u>K-Fluorescent Energy keV</u>	<u>Typical Exposure Rate at 12 cm, mR/hr</u>
Cu	8	10,000
Zr	16	20,000
Cd	24	10,000
La	34	3,000
Sm	43	400
Ta	58	300
Pb	78	200
U	100	200

The monoenergetic radiations from a K-fluorescent X-ray source are used to determine the energy dependence and energy response characteristics of personnel film dosimeters. They will provide a measure of the adequacy of film dosimeter designs for providing exposure evaluations of the general low energy spectrum of X-ray energies encountered by some film dosimeter customers.

Heavily filtered X-rays can be used to evaluate film dosimeter performance in the 50 to 170 keV range. Filters of at least 6 in. on a side are required to provide the large area irradiation field necessary for the test irradiation program. Typically, the filters to be used and the anticipated X-ray output are given in Table C-IV.

The need for Van de Graaff accelerators for X-ray, electron, and neutron irradiation was carefully considered as a part of this study. To equip the Laboratory for the performance of developmental programs in personnel dosimetry, a 3 MeV negative-positive ion convertible accelerator would be

necessary. This item of equipment and the provisions of a properly shielded building for its operation are expensive (estimated cost for building and machine, \$500,000). The functions of the Laboratory can be accomplished and the film dosimeter processor evaluation program can be administered without the procurement of an accelerator.

TABLE C-IV. Typical Filtered X-Ray Radiation Sources

<u>Filter Material</u>	<u>Thickness, ml</u>	<u>Effective Energy, keV</u>	<u>Typical Exposure Rate at 0.5 m, R/hr</u>
Cu	43.5	52	90
Cu	50.2	62	40
Sn	40.0	82	30
Sn	77.5	100	20
Sn	81.0	120	50
Pb	55.0	150	30
Pb	70.0	170	30

Radiation Standardization Equipment

Of prime importance in all operations of the Laboratory is the accurate knowledge of the radiation dose equivalent delivered to each test dosimeter. For all calibrations, the radiation dose equivalent delivered to each test dosimeter needs to be directly related to:

- A radiation source calibration provided by the U. S. Bureau of Standards
- A dose measurement instrument calibrated by the U. S. Bureau of Standards
- A fundamental dose measurement performed with equipment and by methods recommended by the U. S. Bureau of Standards.

In addition to Bureau of Standards calibration of radiation sources, three complete sets of Bureau of Standards calibrated "R" meters should be maintained.

For X-ray irradiations at energies below 50 keV, a standard free air ionization chamber designed in accordance with criteria published by the Bureau of Standards⁽¹⁷⁾ should be used.

Extrapolation chambers with 7 mg/cm^2 windows should be used to measure beta radiation dose from the ^{90}Sr and natural uranium beta radiation sources.

A precision long counter is required for fast neutron fluence standardization. The design of a typical precision long counter suitable for use by this Laboratory is described by DePangher and Nichols.⁽¹⁸⁾

For thermal neutron fluence standardization, activation foil technique should be used. Equipment to count gold, indium and manganese foils and to determine cadmium ratios is required.

Table C-V summarizes the primary radiation standardization equipment that is required by the Laboratory.

TABLE C-V. Radiation Standardization Equipment

<u>Equipment</u>	<u>Number Required</u>	<u>Application</u>
"R" Meters	3 sets	Dose calibrations of high and intermediate energy photons, Radiation Categories 1-A, 1-B, 1-C, 4-A, 4-B
Free Air Ionization Chamber	1	Dose calibrations of low energy photons, Radiation Category 1-D, 4-A
Extrapolation Chambers	2	Dose calibration for beta radiation, Radiation Category 2, 4-B
Precision Long Counter	1	Dose calibration for fast neutrons, Radiation Category 3-A
Activation Foils	5 sets	Dose calibration for thermal neutrons, Radiation Category 3-B

Test Irradiation Dosimeter Jigs

To conduct the test irradiation program the Laboratory will require properly designed and instrumented jigs to position the test dosimeters and the radiation source. In the design of these jigs, the objectives to be considered are:

- Assure accurate and repeatable positioning of test dosimeters
- Assure accurate and repeatable positioning of radiation sources
- Accommodate dosimeters of various sizes and shapes
- Provide a calibration measurement simultaneously with the test exposure
- Verify, by independent measurement, that the intended dose was delivered
- Minimize radiation scatter by using lightweight jigs fabricated of low atomic number materials
- Provide shielding of the radiation source when not in position to make an exposure
- Move the radiation source quickly (a few seconds) into the desired exposure position
- Rotate the radiation source during exposure to provide an isotopic irradiation
- Move the radiation source quickly (a few seconds) into the shielded position when the exposure is completed
- Time the exposure duration
- Provide, with an auxiliary monitor, a graphic record of the exposure duration and intensity.

To conduct the test irradiation program eight test irradiation source holders and dosimeter positioning jigs meeting these twelve objectives are required. These test irradiation program systems are listed in Table C-VI.

TABLE C-VI. Test Irradiation Program System

<u>System Identification</u>	<u>Radiation Source</u>	<u>Radiation Categories of Use</u>
Gamma Radiation Exposure System	Radium-226 Cobalt-60	1-A, 1-B 4-A, 4-B
Gamma Radiation Special Exposure System	Cesium-137 Iridium-192	1-A, 4-A, 4-B
X-ray, Intermediate Energy, Exposure System	X-ray Machine	1-C
X-ray, Low Energy Exposure System	X-ray Machine	1-D, 4-A
Beta Radiation Exposure System (Point Source)	Strontium-90	2, 4-B
Beta Radiation Exposure Systems (Surface Calibration)	Natural Uranium	2, 4-B
Fast Neutron Exposure System	PuBe	3-A
Slow Neutron Exposure System	PuBe	3-B

A typical test irradiation program system for positioning and rotating a small radionuclide radiation source is shown in Figure C-1. This system uses an electronic timer to switch on and off a small vacuum pump which raises the radiation source into the exposure position by vacuum. The air passing the source should be filtered and discharged external to the building to assure that contamination from a possibly ruptured source does not enter the building. Routine monitoring of the in-line filter can serve to detect any possible radiation source leakage. It is not advisable to use air pressure to move the source because possible contamination from a ruptured radiation source could escape the air system and enter the building atmosphere if air in the source positioning system were at a positive pressure with respect to the building atmosphere. At the end of the exposure time, the vacuum pump

FIGURE C-1. Gamma Radiation Exposure System

is shut off by the electronic timer and the source settles quickly, by gravity, to the well shielded position at the base of the air column. This system permits the positioning and exposure of a sizable number (50 to 100) test dosimeters at a time. A calibrated "R" meter is used to measure the actual exposure and a remote radiation monitor provides a chart record of the exposure duration and intensity as a verification of the exposure. Air moving by the radiation source naturally imparts a rotation to it to assure an isotropic exposure. of these test irradiation exposure systems should be provided. One system should be used with a 0.5 Ci radium source for making the exposures in radiation Categories 1-A, 4-A and 4-B. The second system with the 5 Ci cobalt-60 source would be used for making the test exposures required by radiation Category 1-B.

The special radionuclide exposure system shown in Figure C-2 would be used with cesium-137 and iridium-192 sources. It would not be used routinely but only for occasional evaluations at the radiation energies provided by these two sources. The system is consequently not instrumented to the same degree as the routinely used equipment. The radiation source is manually positioned in the source holder using an appropriate source handling tool. The source position and the mobile trolley position are manually controlled from the calibration control station. This system would be used only occasionally for making the test exposures in radiation Categories 1-A, 4-A, and 4-B.

The test irradiation exposures in the intermediate energy range (50 keV to 200 keV) would be made with heavily filtered X-ray radiations with the typical exposure system shown in Figure C-3. This system provides for simultaneous measurement of the exposure at the time of dosimeter irradiation. The "R" meter and exposed dosimeters are continuously rotated to assure identical exposures. The progress of the exposure is

FIGURE C-2. Gamma Radiation Special Exposure Systems

FIGURE C-3. Filtered X-ray Exposure System

estimated from the previously calibrated constant beam monitor. The output from this monitor is recorded to provide a record of the actual exposure. Filters of at least six inches on a side should be used to provide a broad beam suitable for the simultaneous exposure of several dosimeters.

For low energy photon exposures a K-fluorescent radiation source system such as the typical one illustrated in Figure C-4 should be used. This system consists of the "K" X-ray radiators which can be readily changed to provide a range of radiation energies, a constant beam monitor and a rotating dosimeter exposure jig. A free air ionization chamber should be used for the primary calibration. The constant beam monitor is used as a secondary calibration device for determining the dose delivered at each exposure. A chart recorder provides a record of the exposure from the constant beam monitor readout.

For beta radiation test exposures two systems should be available. Processors using a point source calibration with strontium-90 should receive a similar exposure in the test irradiations program. A typical system for making test exposures is shown in Figure C-5. This system requires the use of an extrapolation chamber to measure the beta dose at each position on the exposure arc. Once this is done, a GM tube measurement at a given position can be used to verify each test exposure. An adjustable angle measuring device is used to measure the distance and angle of each dosimeter with respect to the beta radiation source. A chart recorder from the constant monitor provides the record of the exposure.

For processors using a surface beta radiation calibration from a polished uranium slab, a similar exposure should be provided by the Laboratory. A typical system for this exposure is shown in Figure C-6. Dosimeters are positioned in a small rack which is quickly lowered to any desired

FIGURE C-4. "K" Fluorescent X-ray Exposure System

FIGURE C-5. Beta Radiation Exposure System-Point Source

FIGURE C-6. Beta Radiation Exposure System-Broad Source

position above the uranium. Once in the preset position an electronic timer is automatically started. At the duration of the preset time, the dosimeters are quickly removed from the uranium and positioned behind a shielding plate. A GM tube attached to the dosimeter positioning tray provides the verification of the exposure duration and intensity on the chart recorder.

A typical system for making the fast neutron exposures is shown in Figure C-7. The fast neutron PuBe source is positioned manually with an appropriate source handling tool after all the dosimeters are in place. A precision long counter is used to calibrate the system. Constant monitoring and a record of the exposure is provided by a chart recorder responding to the output of a polyethylene moderated BF_3 neutron detector tube. The relatively low intensity of the PuBe neutron source results in long exposure times (hours) which are measured manually. Errors due to the time involved in manually placing and removing the neutron source are not significant.

For thermal neutron test irradiations a sigma pile system as shown in Figure C-8 should be used. The sigma pile should be fabricated of reactor grade graphite and should measure eight feet on a side. The construction of a similar moderator of paraffin or polyethylene and measuring three feet on a side may be substituted for the sigma pile in the interest of economy. For thermal neutron irradiations activation foils are exposed with the dosimeters to provide the thermal neutron fluence determination. A BF_3 tube provides the signal for the chart record of the exposure. The long exposure times required (hours) permit manual handling of the PuBe neutron source without the introduction of significant timing or exposure errors.

FIGURE C-7. Fast Neutron Exposure System

FIGURE C-8. *Slow Neutron Exposure System*

General Instrumentation

A variety of radiation monitoring, contamination survey and calibration control instrumentation will be required. The instrumentation required and the general areas of application are given in Table C-VII.

TABLE C-VII. *General Radiation Instrumentation*

<u>Instruments</u>	<u>Applications</u>
Dose Rate Monitoring	Controlling radiation exposures encountered by laboratory personnel
Contamination Survey	Detection of Alpha, Beta or Gamma contamination
Radiation Source Timing	Controlling of test exposures
Exposure Verification	Assure dose delivery
Area Radiation Status	Indicate radiation conditions in exposure area

Dose rate monitoring equipment, such as Cutie Pies (CP), Junos and neutron detecting instrumentation, is required to determine the radiation fields encountered by the Laboratory staff. For normal Laboratory operation, the instrumentation shown in Table C-VIII is typical of that required. It is, of course, not mandatory that the specifically identified instruments, i.e., CP's and Junos, be used.

TABLE C-VIII. *Typical Radiation Monitoring Equipment*

<u>Dose Rate Instrument</u>	<u>Quantity Required</u>
CP	4
Junos	2
Neutron	2
Beta, Gamma Detection	4
Alpha Detection	4

The Laboratory should make arrangements to have a portable instrument repair service promptly available to keep these

monitoring instruments in good state of repair. All dose rate and detection type monitoring instruments should be recalibrated on a monthly schedule. After any instrument maintenance, a recalibration is required.

Radiation detection equipment to verify that the intended radiation exposures were actually delivered is required for use with each calibration procedure. Good equipment is needed to measure the actual dose delivery time. This equipment should indicate the duration of the radiation measurement directly and should provide on a suitable chart recorder a record trace to verify the exposure time. The chart recorder record should be carefully labeled so that each part of the record can be identified with the specific test irradiation exposures provided.

Electronic equipment to provide fundamental calibration measurements is required in support of the previously discussed calibration equipment. Electrometers are required for use with the free air ion chambers and the extrapolation chambers. Appropriate chart records to record the output of these instruments are also required.

To assure good radiation protection practices in the operation of the Laboratory, an area radiation alarm system should be included in the building design. This system would provide a warning signal at all times when radiation sources are in a raised or "exposed" position and where Laboratory personnel could enter a radiation field in excess of 1 mrem/hr.

5. TYPICAL LABORATORY METHODOLOGY

A brief summary of the typical Laboratory methodology is presented here to characterize the Laboratory operation. Since these are to be considered as typical methods of operation, the Laboratory Director should be authorized to revise these methods as appropriate to meet the needs of the Laboratory, its customers and the AEC.

Many of the methods presented here were tested by actual use in the test irradiation program, and were found to be both practical and necessary to assure the attainment of adequate accuracy in the test irradiations. The principle considerations in their development were for the adequate accuracy of the test irradiations and for the control of the cost and time required for the performance of the test irradiation and evaluation program.

The typical Laboratory operational methods may be divided into the eight major areas:

- Receive and handling test dosimeters
- Calibration of test irradiation systems
- Provide test irradiations
- Return exposed dosimeters
- Evaluation and Reporting of test irradiation results
- Schedule test irradiations
- Maintain Records of Laboratory activities
- Set up internal quality control.

Receive and Handling Test Dosimeters

When dosimeters for test irradiation are received by the Laboratory, they should be promptly surveyed for contamination and placed in the low background, controlled environment vault until the test irradiations are made. A Receiving and Shipping Report should be prepared for each shipment of dosimeters arriving at the Laboratory. A typical Receiving and Shipping

Report is shown on the next page. A test irradiation request number will be issued and recorded on all forms and chart records generated in processing the dosimeters.

Part One of the Receiving and Shipping Report identifies the participating processor, gives his address and the principle contact at the processor's facility for any additional information required. Immediately upon receipt of the dosimeters and before placing the dosimeter in the storage vault, the package should be opened under controlled conditions and a contamination survey performed to assure that all dosimeters are free of radioactive contamination. The contamination survey should be conducted with radiation detection instrumentation capable of detecting the presence of either beta-gamma or alpha radiations in quantities greater than normal background. Prior to use each day, the radiation detection instrumentation should be checked for performance by exposing it to appropriate beta-gamma and alpha response check sources.

In Part Two of the Receiving and Shipping Report, the dosimeters received should be inventoried and the dosimeter numbers assigned by the submitting processor should be recorded opposite the test irradiation scheduled for that group of dosimeters. If calibration film or controls are forwarded with the test dosimeters, these numbers and the total number of dosimeters should also be recorded. Any comments about the condition of the shipment, the dosimeters sent, etc., should be made and a copy of this report sent to the processor to verify that the test dosimeters were received. The form provides space for the logging of the test irradiation exposure run numbers and any different dosimeter identification numbers that the Laboratory may use in the test program. Data relative to the return shipment of the dosimeters completes the form. A copy of the completed form should accompany the return shipment of the irradiated dosimeters. In shipping dosimeters to or from the

RECEIVING AND SHIPPING REPORT

I. DOSIMETERS

Submitted by _____
 Address _____
 City _____
 State _____

Receiving No. _____
 Principal Contact _____
 Telephone _____
 Date Received _____
 Contamination Status
☐ O.K. ☐ REJECT

 II. TEST IRRADIATION DOSIMETERS
 Dosimeter Inventory

<u>Radiation Category</u>	<u>Assigned No.</u>	<u>Total</u>
1. Photons		
A. High Energy		
B. High Dose		
C. Intermediate Energy		
D. Low Energy		
2. Beta		
3. Neutron		
A. Fast		
B. Thermal		
4. Mixtures		
A. Photons		
B. Photons + Beta		

IV. DOSIMETER RUN INVENTORY

<u>Run No.</u>	<u>Assigned No.</u>	<u>Total</u>
----------------	---------------------	--------------

Run Inventory by _____

 III. BLANK CONTROL DOSIMETERS
 Dosimeter Inventory

<u>Radiation Category</u>	<u>Assigned No.</u>	<u>Total</u>
1. Photons		
A. High Energy		
B. High Dose		
C. Intermediate Energy		
D. Low Energy		
2. Beta		
3. Neutron		
A. Fast		
B. Thermal		
4. Mixtures		
A. Photons		
B. Photons + Beta		

V. COMMENTS

VI. SHIPPING DATA

Contamination Status ☐ O.K. ☐ REJECT
 Shipping No. _____
 Date Shipped _____

VII. DISTRIBUTION

- A. Original - Laboratory records.
 B. Copy - Processor after completing Sec. I,II,III
 C. Copy - Processor when dosimeters returned.

Laboratory, all shipments should be made by air express. The packages should be clearly marked as containing unexposed photography film. Test data has indicated that the use of air express for the shipment of film dosimeters results in a minimum buildup of film fog background during shipment. Frequently, conventional rail shipments were made with satisfactory results; however, during the hot summer months, it was not uncommon for excessive film fogging to occur in some rail shipments of some film types.

Calibration of Test Irradiation Systems

Each test irradiation system should be calibrated on a frequency that will assure accurate performance by the Laboratory. The equipment to be used for making the calibrations was reviewed previously. Every test irradiation exposure should be directly related to the latest exposure system calibration.

Each year, one complete set of "R" meter chambers should be sent to the manufacturer for any necessary maintenance and then forwarded to the Bureau of Standards for complete calibrations. When this set is returned to the Laboratory, the other two "R" meter sets should be compared to the newly calibrated "R" meter. The newly calibrated "R" meter should not be used in the routine operation of the Laboratory, but should be set aside as the Laboratory standard to check the performance of the other two "R" meters on a monthly schedule during the year. The most recently calibrated "R" meter set should be used as the standard instrument and the other two "R" meters should be adjusted to match the standard. At any time there is reason to suspect the status of any of the radiation sources, it should be compared with another source at the Laboratory to verify its calibration. On approximately a 3 year schedule, each of these sources should be returned to the Bureau of Standards for recalibration. When a newly calibrated source is returned from the Bureau of Standards, all similar sources should be

compared with the most recently calibrated source. If significant variations in the observed and previously certified values are obtained, the sources in question should be sent to the Bureau of Standards for recalibration. Good source handling and care should assure no difficulties in attaining satisfactory intercomparisons. If frequent difficulties should be observed, the Laboratory Director should immediately review all source handling procedures and reassure himself that proper care and good practices are followed. Experience has shown that radiation sources that receive proper handling and care will maintain their calibration.

The Laboratory should set up Control Charts relating the calibration exposure values measured with time. Initially, each exposure system should be calibrated on a weekly schedule. When the Control Charts demonstrate that good control is attained and the weekly calibration values do not change significantly from the previous weeks calibrations, then longer periods between fundamental calibrations may be established. A verification of each test irradiation exposure is always required by a secondary calibration method which has been described as a part of each exposure system.

Provide Test Irradiations

The test irradiation exposure should be made on the calibrated exposure jigs designed for this purpose. The dosimeters should be placed in the exposure jigs and each location should be measured to assure that the dosimeter is at the correct distance and angle for the proper exposure. Prior to making an exposure a second member of the Laboratory staff should verify that the exposure geometry is correct. Some typical formats for recording the test irradiation and exposure jigs calibration data are shown on the following pages. These are provided to suggest the approach to record the necessary information about each test irradiation. They were designed to provide for:

- Identification of the processor
- Recording exposure system calibrations and necessary calculations
- Test irradiation data
- Exposure verification
- Record of who performed and who verified the work.

Return Exposed Dosimeters

All test irradiated dosimeters should be surveyed to assure that they are free from radioactive contamination, packaged and returned to the processors by air express. The test irradiation should be completed within 10 working days after receipt of the dosimeters, and the dosimeters should be in the return mail within 2 days after the completion of the last test irradiation for any given submission.

Evaluation and Reporting of Test Irradiation Results

A monthly dosimeter test irradiation provides a continuous look at the performance of each processor. Each month each processor should send to the Laboratory the number of dosimeters prescribed in the next section. The blank films should be stored in the film dosimeter storage vault while at the Laboratory, to be returned with the test irradiated dosimeter shipment. Each processor should evaluate the blank film to assure that good shipment and storage conditions are experienced, and that fogging or unexplained abnormal "darkening" of the film does not occur. It is possible that an evaluation of the blanks will indicate that excessive abnormalities in film darkening has occurred. In this event, the processor should promptly notify the Laboratory of the situation. The Laboratory will make a judgment as to the necessity of a retest based on the results. All fogged film should be returned to the Laboratory for study, and an attempt should be made to determine the cause of the difficulty and to prevent future trouble.

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Radiation Categories: 1-A, 1-B, 4-A, 4-B

Exposure Systems No. _____

Temperature: _____
 Start: _____
 Finish _____
 Ave. _____

Chamber Reading _____
Total Correction Factor _____
Corrected Exposure _____

[illegible]

Checked by

TEST IRRADIATION EXPOSURE

Radiation Category: 1-C

I. Processor _____
Date _____

Test Irradiation Request No. _____
Exposure System No. _____

II. X-RAY MACHINE SETTINGS

KVP _____
mA _____
Voltage _____

Filament _____
Filters Used: _____
Material _____
Thickness _____

III. EXPOSURE SYSTEMS CALIBRATION

"R" Meter Used _____
Chamber No. _____
B. of Std. Correction Factor _____
B. of Std. Certification Date _____

"R" Meter Run Data:
Time On _____
Time Off _____
Total _____

Pressure - Start _____
Finish _____
Ave. _____

CALCULATIONS:

$$f = 2.576 \left(\frac{273 + t}{p} \right) F$$

f = Total Correction Factor
t = Temperature °C
p = Pressure, run Hg
F = Chamber Correction Factor from
B. of Std.

Temperature - Start _____
Finish _____
Ave. _____

Chamber Reading _____
Total Correction Factor _____
Corrected Exposure _____

Calculated by _____
Checked by _____

IV. TEST IRRADIATION DATA:

<u>Dose Delivered</u>	<u>Dosimeter No.</u>	<u>Exposure Time</u>
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____
_____	_____	_____

Performed by _____ Checked by _____
Audit chart identified, checked, and
added to Exposure folder by _____

TEST IRRADIATION EXPOSURE
Radiation Category: 1-D, 4-A

I. Processor _____ Test Irradiation Request No. _____
Date _____ Radiation Category For This Test _____
Exposure Systems No. _____

II. X-RAY MACHINE DATA

Line Voltage _____ "K" Fluorescence Source Data
Filament Current _____ Filter Used _____
KVP _____ Distance of Exposure _____
mA _____

III. EXPOSURE SYSTEMS CALIBRATION

Free Air Ionization Chamber
Distance from X-ray _____
Output Current _____
Factor _____
Dose Rate _____

Pressure:
Start _____
Finish _____
Ave. _____

Temperature:
Start _____
Finish _____
Ave. _____

Calculations:

Calculated by _____ Performed by _____

IV. TEST IRRADIATION DATA:

<u>Dose Delivered</u>	<u>Dosimeter No.</u>	<u>Exposure Time</u>	<u>Beam Current Rate</u>
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____

Performed by _____ Checked by _____
Audit chart checked, identified, and added to
to exposure folder by _____

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I. Processor _____
Date _____

Test Irradiation Request No. _____
Radiation Category for this test _____
Exposure Systems No. _____

Surface dose rate of polished natural uranium is taken to be 225 mrad/s 1 hour.

[illegible]

Performed by _____
Audit chart checked, identified, and added to
exposure folder by _____

Checked by _____

I. Processor _____ Test Irradiation Request No. _____
Date _____ Radiation Category for this test _____
Exposure Systems No. _____

Chamber Factor
Correction Calculation:

[illegible]

Checked by

The Laboratory will evaluate test irradiation results by the procedure detailed in Appendix B. The statistical method will evaluate the bias and variance observed, with the bias correction factors supplied if necessary. The decision-making outline presented will be followed to determine if the observed performance meets the performance criteria. A continuous record of performance will be kept and used to determine the level of performance. Initially, the data collected in any one year on the monthly program will be used to determine the performance. To simplify the data handling, the year will be a given 12 month period; not a running 12 month period. The statistical program is planned so that a year's test can be combined to evaluate performance. This results in the use of a minimum number of test dosimeters for the performance evaluation.

If after a given set of monthly performance checks, the performance does not meet the performance criteria, the processor will be promptly notified. No further action will be initiated by the Laboratory for failure on a single monthly test. If on the test the following month a failure occurs again in that same radiation category, the processor will be immediately notified and requested to send in a full set of dosimeters for test in the failed radiation category. This full set of test dosimeters should be received within 2 weeks after they are requested. If on evaluation of this performance check, a satisfactory level of performance is attained, the Laboratory should ask for an explanation of what was changed and should return the processor to the routine monthly test schedule. The previously collected monthly data will be disregarded and a new 12 month test evaluation period will be started. If, however, the first full set of test dosimeters also result in a failure to meet the performance criteria, the processor should again be promptly notified and a second full set of test dosimeters requested in this category. Again, these should be

received within 2 weeks of the date of request. If this second set of test evaluations show performance meeting the performance criteria, the Laboratory should request an explanation for the improved performance and, if satisfactory to the Laboratory Director, the processor should be returned to the routine monthly schedule. If the second full test is failed, the processor should be notified and the appropriate regulation body or bodies should be informed that the processor has failed to maintain performance at the level required by the performance criteria. The Laboratory should take no further action with respect to the performance test failure.

After having failed two full test sets, it should then be mandatory that a processor pass two consecutive full test sets to be reinstated as having met the performance criteria.

The design of the statistics which assure that an adequate performer should pass the test also give a rather good chance for a poor performer to pass on any one test. The requirement of two consecutive tests is designed to give an adequate performer every reasonable chance to pass and continue to pass the test, but prevent inadequate performers from becoming identified as meeting the performance criteria.

This schedule of tests should provide the lapse of four months from the time a failure is noted until a decision is made that unsatisfactory performance has been established. This should be a reasonable time for a sincere processor to locate any difficulty and correct the problem.

Initially, any processor passing the first full test is identified as meeting the performance criteria. This gives all processors the best chance to make a good start, gives an inadequate processor a good chance to meet the performance criteria and make the necessary improvements to continue to meet the criteria. With this Laboratory startup procedure,

an inadequate processor who fails to make the necessary improvements should be identified in about six months. A grossly inadequate processor should not be able to meet even the initial test and, hence, will not be identified as meeting the performance criteria.

The schedule of events for processors of various performance levels and the timing is shown in the following tables:

TABLE C-IX. *Processor that Immediately and Continually Meets Performance Criteria*

Example 1

<u>Event</u>	<u>Time, month</u>	<u>Action</u>
1) Startup of Laboratory	0	Send in full test sets
2) Reports of 1st results	1	Passes, verified as meeting performance criteria placed on monthly test program
3) Monthly test	2	Passes, send in dosimeters for monthly test
4) Monthly test	3	Passes, send in dosimeters for monthly test
.	.	.
.	.	.
.	.	.
13) Monthly test	12	Passes, send in dosimeters for monthly test. New yearly accumulation of monthly data begins
14) Monthly test	13	Passes, send in dosimeters for monthly test
.	.	.
.	.	.
.	.	.
.	.	.

TABLE C-X. *Processor that Does Not Meet Performance
Criteria at Every Test Period*

Example 2

<u>Event</u>	<u>Time, month</u>	<u>Action</u>
1) Startup of Laboratory	0	Send in full test sets
2) Report of 1st results	1	Failed - send in a second full test set
3) Report of 2nd results	2	Passed - verified meeting performance criteria on monthly test program
4) Monthly test	3	Passes - send in dosimeters for monthly test
5) Monthly test	4	Passes - send in dosimeters for monthly test
6) Monthly test	5	Fails - send in dosimeters for monthly test. This data set aside and not used in continuing analysis of yearly accumulated data
7) Monthly test	6	Passes - send in dosimeters for monthly test
.	.	.
.	.	.
.	.	.
.	.	.
13) Monthly test	12	Passes - send in dosimeters for monthly test. New yearly accumulation of monthly data begins
.	.	.
.	.	.
.	.	.
.	.	.
14) Monthly test	13	Passes - send in dosimeters for monthly test
.	.	.
.	.	.
.	.	.
.	.	.

TABLE C-XI. *Processor that Initially Meets Performance Criteria but Fails Later*

Example 3

<u>Event</u>	<u>Time, month</u>	<u>Action</u>
1) Startup of Laboratory	0	Send in full test set
2) Report of 1st results	1	Failed - send in a second full test set - This data set aside and not used in continuing analysis of yearly accumulated data
3) Report of 2nd results	2	Passes - verified as meeting performance criteria - place on monthly schedule
4) Monthly test	3	Passes - send in dosimeters for next monthly test
5) Monthly test	4	Passes - send in dosimeters for next monthly test
6) Monthly test	5	Fails - send in dosimeters for next monthly test - This data set aside and not used in continuing analysis of yearly accumulated data
7) Monthly test	6	Fails - Laboratory request full test set - This data set aside and not used in continuing analysis of yearly accumulated data
8) Full test set	7	Fails - Laboratory request second full test set - This data set aside and not used in continuing analysis of yearly accumulated data
9) Full test set results	8	Fails - Laboratory identifies to regulatory agencies that processor fails to meet performance criteria. Laboratory will continue to provide test irradiations if requested by processor. If and when processor passes two consecutive tests processor will be identified as meeting performance criteria and placed on monthly test program again

TABLE C-XIIa. *Processor that Meets Performance
Criteria and Nearly Fails Later*

Example 4

<u>Event</u>	<u>Time, month</u>	<u>Action</u>
1) Startup of Laboratory	0	Send in full test set
2) Report of 1st results	1	Failed - send in a second full test set. This data set aside and not used in continuing analysis of yearly accumulated data
3) Report of 2nd results	2	Passes - verified as meeting performance criteria - place on monthly schedule
4) Monthly test	3	Passes - send in dosimeters for next monthly test
5) Monthly test	4	Passes - send in dosimeters for next monthly test
6) Monthly test	5	Failed - send in dosimeters for monthly test. This data set aside and not used in continuing analysis of yearly accumulated data
7) Monthly test	6	Failed - Laboratory request full test set. This data set aside and not used in continuing analysis of yearly accumulated data
8) Full test set results	7	Failed - Laboratory request second full test set. This data set aside and not used in continuing analysis of yearly accumulated data
9) Full test set results	8	Passes - Laboratory asks for explanation - if acceptable places on monthly schedule - if not acceptable, request a third full set. If passed, then placed on monthly schedule. If failed, is placed in same status as Example 3, Event 9
10) Monthly test	9	Passes - send in dosimeters for next monthly test
.	.	.
.	.	.
.	.	.

TABLE C-XIIb. *Processor that Fails to Meet Performance Criteria*

<u>Example 5</u>		
<u>Event</u>	<u>Time, month</u>	<u>Action</u>
1) Startup of Laboratory	0	Send in full test sets
2) Report of 1st results	1	Failed - send in second full test set. This data set aside and not used in continuing analysis of yearly accumulated data
3) Report of 2nd results	2	Failed - not verified as meeting performance criteria. Placed in same status as Example 3, Event 9

The Laboratory test and action procedures for verifying and not verifying processors as meeting performance criteria are summarized below:

1. At startup of the Laboratory, each processor should pass one full test irradiation set in each radiation category to be verified as meeting performance criteria in that category. If the first test irradiation is passed, the processor will be placed on monthly test schedule. If the first test set is failed, a second full test irradiation set should be provided and if passed, the processor should be treated the same as if the first set was passed.
2. Once on the monthly test schedule, the data from two consecutive monthly tests combined with the data from the other monthly test collected over a 12 month period must indicate a failure to meet the performance criteria to require the need for a full test irradiation set. Two consecutive full test sets must be failed to merit an identification as failing to meet the performance criteria. A four month time period is provided between the first test failure and the decision that the performance criteria are not being met.

3. Once two consecutive full tests have been failed, then two consecutive full tests must be passed to meet the performance criteria.

Schedule of Test Irradiations

Each processor is to be tested on a routine basis on a one month frequency. This provides an even workload for the Laboratory, but more importantly, provides a continual check on processor performance. This continual checking makes it difficult for a processor to give special effort to the test dosimeters and renders special blind audits generally unnecessary. In view of the monthly performance test recommended, special blind audits are not proposed.

After the initial test, the number and types of dosimeters to be sent to the Laboratory can be determined from Table C-XIII and the radiation categories in which performance is to be verified.

TABLE C-XIII. *Monthly Dosimeter Requirements*^(a)

<u>Radiation Category</u>	<u>Full Test Set</u>	<u>Monthly Test Set</u>
1. Photon		
A. High Energy	28	4
B. High Dose	24	2
C. Intermediate Energy	28	3
D. Low Energy	14	2
2. Beta	20	3
3. Neutrons		
A. "Fast"	24	3
B. Thermal	12	2
4. Mixtures		
A. Photons	20	2
B. Photons + Beta	20	2

(a) *Three film blanks should be sent with each dosimeter shipment to the Laboratory.*

Each processor should routinely send to the Laboratory, once each month, the number of dosimeters indicated in this table for each radiation category in which a service is offered. The Laboratory should schedule these submissions to avoid all of these dosimeters arriving at the first of each month. The Laboratory should, of course, provide the neutron exposures to the neutron dosimeters, however, the processor should not be informed which of the other dosimeters were exposed in which category. The Laboratory may choose to expose all of the submitted dosimeters to radiations in a single radiation category, however, general Laboratory practice would provide some exposures in each radiation category each month.

Records of Laboratory Activities

A complete record of the technical activities of the Laboratory should be maintained. The more significant technical records to be maintained are:

- Receipt and shipment of test irradiation dosimeters
- Dose received (if any) while stored at the Laboratory.
This record should verify that the dosimeters received only the intended dose while at the Laboratory.
- Test irradiation data including exposure system used, its calibration, verification chart, and signature of who performed the work and who verified it
- Radiation source calibration certificates and measurement data, recalibration schedules
- Incoming test-irradiation exposure evaluation data
- Evaluations of data by the Laboratory including record of bias and variance measurements and bias correction factors supplied to processors
- All reports of performance to regulatory agencies and processors
- Continuous evaluations of processor performance and trends toward improving or deteriorating performance.

The Laboratory records need not be maintained indefinitely. They should be destroyed on a schedule identical to that in effect for personnel dose records. All records should be kept on a strictly-private basis and are to be discussed only with the service for which the record was generated. Only the approval or disapproval status of a service is to be considered as "public knowledge" and outside of the "strictly-private" domain.

Internal Quality Control of Laboratory

The Laboratory should set up a complete set of quality controls and control charts to maintain a continuous record of the performance of the Laboratory. These charts should relate the primary radiation calibrations and secondary radiation calibrations with time. These measurements should also be related directly to the verifications of exposure measurements made for each test exposure by appropriate quality control charts. The exact form and number of charts to be maintained should be established by the Laboratory Director.

The need for a third party audit of the Laboratory to assure its adequate performance was considered. Although this may be desired from time to time, it is not necessary to establish a firm procedure or schedule for such an audit. The double check system of Laboratory operation and the frequent contacts with the Bureau of Standards should assure adequate Laboratory performance.

Any audit team for the Laboratory should be appointed on a one-time basis and should include a representative from the various types of processors and two independent representatives not currently processing film.

The Laboratory should publish all of its detailed standard operating procedures. This publication gives its customers and others an opportunity to comment on the methods.

The Laboratory should consider all comments received and adopt those that may improve its overall quality control and performance.

In the foregoing sections of this report, the exposure level, E, has been treated as though it were some known "true" value for film badge exposures. It is recognized; however, that the intentional exact reproduction of a radiation exposure is highly improbable. The successive attempts to reproduce an exposure actually yield varying exposures depending upon the system of reproduction.

The differences in the exposures of the test badges will be reflected in the measurements submitted by the processor. So, not all sources of deviation of measurements from exposure levels are sources inherent in the measurement process. Is it sensible, then, to test and correct for systematic bias when the exposure levels used for analysis may not be some "true" values of exposure? Is it fair, then, to judge the quality of a measurement process on the basis of an estimate of its variance when part of the variation estimated is not due to the process itself? The answer to both questions is yes.

Corrections for systematic bias are always with reference to some nominal (reference or standard) value which has been established by some presumably "more accurate" measurement process, or which has been established by definition. The purpose of such corrections is, of course, to create more agreement amongst measurements of the same kind made with different processes. The intent of the bias correction recommended is to achieve this purpose. The corrections are with reference to measurements of exposure level made with R-meters, free-air ionization chambers and extrapolation chambers.

With regard to the testing of the variance of a film badge dosimetry measurement process, the criteria developed allow for

the variation introduced by the exposure technique. The criteria values, κ , were established using the variance estimates, S_i^2 , from data containing the variation due to exposure. Hence, the criteria values are larger than they would be if the variation due to exposure were zero, and, in effect, the values provide a test for measurement process variance which is independent of the variation in the exposures. This last comment will be true as long as the exposure variance at each exposure level remains constant. It will be the responsibility of the Laboratory to maintain a check on the variation introduced by its exposure techniques.

Two techniques for exposing a number of film badges at the "same" level are: (1) expose the badges one at a time in a fixed jig position, and (2) expose the badges simultaneously in different jig positions for a fixed length of time. The equipment used for exposing the film badges involved in the Industry Study employs both techniques. Experiments were performed on this equipment to estimate the components of film badge dosimetry measurement variance due to the time and position variables.

Sixty badges were exposed at a single level on each piece of equipment. The components of variance due to position effects and repetitions (time differences) were estimated by Analysis of Variance⁽⁹⁾ procedures (Section 7.53). The estimates of the components of variance and their percentages of the total measurement variance are shown in Table C-XIV.

The "% of Total" figures provided useful information for the design of the equipment recommended for the Film Dosimetry Calibrations Laboratory. When that equipment has been constructed, experiments should be performed and the results compared with the results of these experiments in order to insure against excessive measurement variation being introduced by the Laboratory.

TABLE C-XIV. *Estimates of Position and Reproducibility Components of Variance for Exposure Equipment and Their Percentages of the Total Measurement Variance*

<u>Source</u>	<u>Exposure Level</u>	<u>Position Component Estimate, mrem²</u>	<u>% of Total</u>	<u>Repetition Component Estimate, mrem²</u>	<u>% of Total</u>
Ra	240 mrem	3	1	7	2
⁶⁰ Co	23000 mrem	0	0	0	0
170 keV X-ray	240 mrem	125	48	4	1
100 keV X-ray	240 mrem	116	21	142	26
17 keV X-ray	120 mrem	-(a)	-	0	0
U	240 mrad	56	13	0	0
Sigma Pile	120 mrem	1.5	3	12	23
PuBe	525 mrem	12	12	0	0

(a) *The 17 keV X-ray equipment used rotating positions to eliminate position effects*

After calibration and testing of the Laboratory equipment has been completed and the exposure positions "fixed," a quality control program should be initiated. For each exposure position on a jig, quality control charts can be constructed from calibration instrument measurements.⁽⁹⁾ The cited reference (Section 10.55) explains the construction and use of the charts for controlling the instrument; however, the same charts are applicable to the control of the exposure levels. That is, when an instrument measurement signals that control has been lost, both the instrument and the exposure apparatus should be investigated for assignable causes before proceeding with routine exposures. The control charts will constitute a continuing record of the exposure control exercised by the Laboratory.

Statistical procedures for internal control by the Laboratory have been outlined here in the form of the general features of experimental and quality control programs. The details of these programs will depend upon the final version of the equipment and the desired operating cost for the Laboratory.

6. PROPOSED LABORATORY STAFF

The Film Dosimetry Calibration Laboratory staff should consist of a Director, an Engineer, a Technician and a Secretary. This provides a staff of two technical persons to look after the technical aspects of the Laboratory and one technician to assist in the performance of the routine aspects of the Laboratory test irradiation program. The work of the Laboratory should be above reproach, and a competent staff of recognized capability is required to assure this status. Of course, the work of the Laboratory can be no better than the capabilities of its staff.

The qualifications of each member of the Laboratory will require careful consideration to assure that an experienced and capable staff are obtained. It is not a feasible plan to staff this type of Laboratory with inexperienced personnel no matter what degree of technical proficiency they may have attained. The qualifications of the staff are summarized in the following sections:

Laboratory Director

The Director shall have a degree in one of the sciences-- physics, chemistry, mathematics or engineering. He shall have a minimum of five years of practical experience in personnel film dosimetry programs. He requires a thorough and demonstrated knowledge of film dosimetry practices including dosimeter processing, evaluation, design, development and film dosimeter performance characteristics. He should have a background in health physics to appreciate the many problems that

may be encountered in personnel film dosimeter programs. In addition to his technical competence in the area of film dosimetry, he should have interest, experience and capability with other dosimetry techniques. He should be acquainted with current progress in thermoluminescent dosimetry and radiophotoluminescent dosimetry. He should understand the basic principles involved and be competent in the use of primary radiation calibration equipment. For example, he should be competent in the use of free air ionization chambers, extrapolation chambers, R-meters, precision long counters and similar radiation measuring equipment so that fundamental calibrations can be provided. He should possess a good understanding of statistics and the application of statistics and mathematical analysis to the personnel film dosimetry evaluation program. He should have demonstrated good administrative capabilities, write well and work well with people.

Engineer

The Engineer should have earned a degree in one of the sciences, physics, chemistry, mathematics or engineering. A minimum of two years of experience in the field of personnel film dosimetry with intimate knowledge of the processing and evaluation of film dosimeters is required. In general, the Engineer should have knowledge, experience and capability in all areas prescribed for the Director, but to a somewhat lesser degree.

Technician

One Technician will be required to assist in making the test exposures and the preliminary evaluation of some of the test data. The capabilities and experience of the Technician should lie in the fields of physical sciences. Experience in personnel film dosimetry and radiation protection or health physics activities is desirable, but not mandatory.

Secretary

A Secretary will be required for the organization. She should have the qualifications established for advanced secretarial positions. Her duties will include the preparation, filing and maintenance of the record copies of the test exposures as well as the conventional secretarial duties as directed by the Laboratory Director and the Engineer.

7. BUSINESS VOLUME

The business volume of the Laboratory is estimated from the total number of processors of all types in the United States and the number of dosimeters required by the Laboratory in each radiation category. Table C-XV shows the number of processors of the three types (commercial, AEC Laboratory, and military) and the estimated number of each of these processors that might expect to participate in the performance approval plan.

TABLE C-XV. *Number of Major Processors*

<u>Type</u>	<u>Total Number</u>	<u>Anticipated Participants</u>
Commercial	15	11
AEC Laboratories	21	21
Military	9(a)	9(a)
Total	45	41

(a) *The military has many small dosimeter processing stations not included in this entry.*

The number of processors expected to participate in the Laboratory program by radiation category is shown in Table C-XVI.

For the initial test irradiation program, the same number of test dosimeters used in this study should be required in each radiation category. The number of dosimeters required by radiation category and the total number anticipated on the basis of the participation estimated in Table C-XVI is shown in Table C-XVII.

TABLE C-XVI. *Potential Participants in Laboratory Program by Radiation Category*

<u>Radiation Category</u>	<u>Commercial</u>	<u>AEC</u>	<u>Military</u>	<u>Total</u>
1. Photon				
A. High Energy	11	21	9	41
B. High Dose	11	21	9	41
C. Intermediate Energy	11	15	8	34
D. Low Energy	10	10	5	25
2. Beta	11	20	8	38
3. Neutrons				
A. "Fast"	10	15	7	32
B. Thermal	8	5	4	17
4. Mixtures				
A. Photons	5	10	5	20
B. Photons + Beta	11	20	8	38
Total Number of Test Irradiation Sets				286

TABLE C-XVII. *Probable Dosimeter Requirements for Initial Test Irradiation*

<u>Radiation Category</u>	<u>Dosimeter Required</u>	<u>Total Participants</u>	<u>Total Dosimeters in Test Program</u>
1. Photon			
A. High Energy	28	41	1148
B. High Dose	24	41	984
C. Intermediate Energy	28	34	952
C. Low Energy	14	25	350
2. Beta	20	38	760
3. Neutrons			
A. "Fast"	24	32	768
B. Thermal	12	17	204
4. Mixtures			
A. Photons	20	20	400
B. Photons + Beta	20	38	760

The total number of dosimeters required for tests in all categories is 190 per participant. The total number of dosimeters to be involved in the first test irradiation program is 6326.

8. ESTIMATED LABORATORY COST

The method of financing the construction, equipping and operation of the Film Dosimetry Calibration Laboratory is markedly dependent on the course of action taken to establish the Laboratory and on the actual current capabilities of the group selected to start up and operate the Laboratory. The selection of a Laboratory operator who currently lacks the facilities to provide the functions of the Laboratory will require construction and equipment procurement cost to provide the necessary features of the Laboratory. On the other hand, there are a number of groups within the United States who have the basic facilities now in place to administer a program of this type. Only slight modifications or additions would be required to render such facilities ready and fully capable of providing the functions prescribed for the Film Dosimetry Calibration Laboratory.

Estimated Laboratory Construction Cost

Land

The cost of purchase or lease of land for construction of a Laboratory is dependent on the part of the country where the Laboratory is to be constructed and the location of the Laboratory with respect to the surrounding urban area. A lot of 10,000 to 50,000 ft² would be required to provide some surrounding area for parking and building access control. Cost could vary from as low as a few thousands of dollars to several tens of thousands of dollars for the land, depending on the location factors. Cost for utilities access could be comparable to the land acquisition cost.

Laboratory Building

The floor area of the building is determined by the requirements for irradiation rooms, office space, shipping and receiving area, and vaults. Space allotment as shown in Table C-XVIII provides an estimate of the total building size.

TABLE C-XVIII. *Laboratory Building Space*

<u>Room Designation</u>	<u>Number</u>	<u>Size Each, ft²</u>	<u>Total Area, ft²</u>
Irradiation Room	1	900	900
Irradiation Room	1	400	400
Offices	4	200	800
Shipping & Receiving	1	300	300
Vaults	2	100	200
Subtotal			2,600
Support Space (halls, heat and ventilation, wash rooms, etc.) at 40% of useful space)			1,040
Total Floor Space			3,640

Construction cost for the Laboratory, including the pouring of the concrete vaults and concrete shielding walls between the irradiation rooms, is estimated at \$40/ft². The total estimated construction cost, including a design cost of 10% and a contingency of 12.5%, is shown in Table C-XIX.

TABLE C-XIX. *Laboratory Construction Cost*

<u>Item</u>	<u>Rate</u>	<u>Total Cost</u>
Laboratory	3,640 ft ² @ \$40	\$ 145,600
Design	10% of Laboratory Cost	14,560
Subtotal		160,160
Contingency	12.5% of Total Cost	20,020
Total		\$ 180,180

The total estimated construction cost of the Laboratory would be about \$180,000

Estimated Equipment Cost

The cost of the equipment was determined from construction cost estimates for fabricating the typical exposure jigs shown

earlier, the cost of purchasing the radiation sources and X-ray machines, and dose measurement and control equipment. These estimates are summarized in Table C-XX.

TABLE C-XX. *Equipment Cost Estimates*

<u>Item</u>	<u>Number Required</u>	<u>Total Cost</u>
1. Exposure Systems		
a. Radionuclide, Photon Exposure Systems	2	\$ 3,000
b. Radionuclide, Photon, Special Exposure System	1	500
c. X-ray, Intermediate Energy Exposure System	1	1,750
d. X-ray, Low Energy Exposure System	1	2,500
e. Beta Radiation Exposure System (Point Source)	1	1,750
f. Beta Radiation Exposure System (Surface Calibration)	4	2,000
g. Neutron, Fast, Exposure System	1	2,500
h. Neutron, Thermal Exposure System (Polyethylene Moderator)	1	1,500
	Total	\$ 15,500
2. Calibration Sources		
a. Radium (0.5 Ci)	2	8,000
b. Radium (0.01 Ci)	2	160
c. Cobalt-60 (5 Ci)	1	325
d. Cobalt-60 (1 Ci)	1	250
e. Cobalt-60 (0.2 Ci)	1	180
f. Cesium-137 (1 Ci)	1	400
g. Iridium-192 (1 Ci)	1	200
h. Strontium-90 (0.003 Ci)	2	250
i. Strontium-90 (0.0001 Ci)	2	200
j. Uranium (8 x 1 x 1/4 in.)	20	400
k. PuBe (80 g Pu)	2	3,140
	Total	\$ 13,505

TABLE C-XX (contd)

<u>Item</u>	<u>Number Required</u>	<u>Total Cost</u>
3. Calibration Machine		
a. 50 to 300 kV X-ray	1	\$ 18,200
	Total	\$ 18,200
4. Calibration Standardization		
a. "R" Meter Sets	3	4,500
b. Extrapolation Chambers	3	4,200
c. Free Air Ion Chamber	1	5,000
d. Precision Long Counter	1	8,000
e. Activation Foil Sets	5	500
f. Electrometer Standard	1	1,000
g. Time Standard	1	800
	Total	\$ 24,000
5. Radiation Control Instrumentation		
a. Beta, Gamma Dose Rate Monitoring	4	800
b. Neutron Dose Rate Monitoring	2	1,200
c. Beta-Gamma Detection	4	1,200
d. Alpha Detection	4	1,200
e. Area Monitors	2	1,500
	Total	\$ 5,900
6. Office Furniture and Equipment	Total	\$ 9,300
7. Miscellaneous		
a. Source Storage Casks	8	5,000
b. Vault Air Sampler	1	500
c. Source System Air Samplers	2	1,000
d. Air Filter Counter	1	500
e. Monitoring Instrument Calibration Jigs	3	1,500
f. Constant Voltage Transformers	5	2,500
	Total	\$ 11,000

Table C-XXI summarizes the cost of providing a suitable Film Dosimetry Calibration Laboratory.

TABLE C-XXI. *Laboratory Provision Cost Comparisons*

<u>Item</u>	<u>Cost Estimates</u>
Land	\$ 10,000
Laboratory Building	180,000
Exposure Systems	15,500
Calibration Sources	13,500
Calibration Machines	18,200
Calibration Standardization	24,000
Radiation Control Instrumentation	5,900
Office Furniture	9,300
Miscellaneous	11,000
Total	\$ 287,400

Estimated Operational Cost

The cost for the routine operation of the Laboratory was estimated. The estimates are made by considering the cost of maintaining the necessary staff, facility and equipment.

To secure personnel with the capabilities and experience required for the proper operation of the Laboratory and to assure the quality of the Laboratory, the salary schedule shown in Table C-XXII is recommended. This schedule is consistent with salary reviews of industry for the quality of staff members required for each position.

TABLE C-XXII. *Direct Salaries*

<u>Staff</u>	<u>Salary Range</u>
Director	\$ 14,000-18,000
Engineer	10,000-15,000
Technician	6,000-10,000
Secretary	5,000- 7,000
Totals	\$ 35,000-50,000

The operating cost of the Laboratory presented in Table C-XXIII was estimated by using the experience attained in performing the test irradiation program and operating similar facilities. The total cost estimate is about \$145,000.

TABLE C-XXIII. *Laboratory Annual Operating Cost*

<u>Item</u>	<u>Cost Estimate</u>
Salaries	\$ 40,000
Benefits @ 15% of Salaries	6,000
Building	
Maintenance	10,000
Utilities	10,000
Depreciation	
Building, \$180,000 over 40 yr	4,500
Equipment, \$97,400 over 10 yr	9,740
Supplies	
Laboratory	5,000
Office	2,000
Support Services	10,000
Travel	1,200
Equipment Maintenance	5,000
U. S. Bureau of Standards	5,000
Shipping and Receiving	2,000
Subtotal	<hr/> \$ 110,440
Profit @ 8% of Operation Cost plus 6% of Investment	26,080
Capital Equipment Additions	10,000
Total	<hr/> \$ 146,520

APPENDIX D

BIAS AND RELATIVE ERROR DATA TABLES

APPENDIX D

BIAS AND RELATIVE ERROR DATA TABLES

The summary of the data collected in the test irradiation program is provided in this section. The relative errors expressed as percent of dose and the bias expressed as percent of dose are tabulated for each test irradiation. In the tables, a "dash" entry indicates that the processor did not participate in that part of the study. A zero entry indicates that a zero relative error or bias was observed.

TABLE D-I. Test Irradiation - Radium Gamma Radiation

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$					Bias as % of Dose				
	Dose in mrem					Dose in mrem				
	60	120	240	500	1000	60	120	240	500	1000
1	10	9.6	11	15	10	20	21	16	14	-3.7
2	16	9.6	9.7	6.1	4.1	18	-4.2	-1.3	-17	-26
3	17	9.5	11	11	7.7	-13	-4.2	2.1	8.0	3.6
4	40	32	25	8.1	21	22	4.2	5.0	5.2	1.8
5	38	46	11	7.4	6.6	67	19	1.3	-6.6	-5.4
6	15	5.8	2.7	2.6	4.9	-25	-25	-25	-20	-15
7	32	16	9	7.7	9.3	-13	2.5	6.3	12	18
8	0	60	34	12	8.8	-100	-61	-32	-28	-23
9	0	14	4.3	2.1	3.8	33	17	2.9	-7.0	-13
10	0	25	13	4.1	4.9	8.3	6.7	-3.3	-7.4	-9.8
11	14	7.9	6.3	4.8	4.4	-42	-41	-39	-44	-47
12	16	5.2	6.1	7.7	7.1	57	24	14	15	7.4
13	0	4.1	6.8	3.2	0.5	-17	-12	-15	-16	-8.5
14	17	10	6.8	4.3	1.2	-38	-22	-14	-6.0	-7.1
15	17	17	3.4	1.6	3.9	5.0	13	5.0	3.6	-0.9
16	17	16	6	10	16	70	28	-2.1	-13	-15
17	31	38	27	11	7.4	-10	-7.5	9.2	-3.4	-8.1
18	8.3	4.3	3.4	3.1	6.5	-73	-51	-31	-26	-17
19	34	24	10	11	4	48	33	23	24	18
20	35	15	19	11	5.3	6.7	8.3	12	18	7.5
21	-	-	-	-	-	-	-	-	-	-
22	17	9.6	6.2	4.3	3.0	22	-4.2	-7.5	-10	-9.4
23	16	4.8	9.2	2.4	1.0	-27	-23	-17	-16	-24
24	15	13	6.4	6.6	6.0	-3.3	0	-1.7	-2.2	-3.4
25	42	16	8.5	6.1	5.9	40	11	2.5	-2.0	-8.8
26	9.6	0	1.7	1.6	0.1	-13	-8.3	-3.8	-1.6	3.0
27	0	4.8	4.3	1.9	1.4	-8.3	-2.5	-0.8	1.2	1.3
28	3.3	8.7	2.7	2.4	1.9	17	1.7	7.9	10	8.6
29	0	14	4.3	4.1	2.7	17	17	14	11	-2.9
30	30	36	20	25	7.6	-22	-10	-8.8	-1.6	-7.6
31	17	0	4.5	4.3	6.8	22	17	6.3	-4.0	-10
32	13	9.6	3.4	1.6	0.1	3.3	4.2	3.3	0.4	-0.1
33	59	17	7.6	13	12	-20	17	6.7	11	9.6
34	33	32	6.6	2	1.8	-92	-71	-39	-28	-25
35	41	8.3	12	3.2	4.1	-33	-19	-26	-20	-17

TABLE D-II. Test Irradiation - Cobalt-60 Radiation

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	40,000	100,000	600,000	40,000	100,000	600,000
1	4	2	-	13	27	-
2	5	1	14	-98	-99	-99
3	0	0	1	23	10	-8.7
4	13	0	16	28	16	17
5	4	7	-	-17	-11	-
6	6	14	19	-6.8	-5.6	1.7
7	3	4	17	30	-0.9	-9.7
8	32	34	21	-33	-13	-50
9	9	4	27	-7.8	-15	-6.3
10	0	7	-	-5.0	-12	-
11	1	1	5	-38	-50	-70
12	3	1	6	-11	-16	-23
13	0	6	10	0	29	43
14	6	3	-	-3.8	-12	-
15	3	4	-	-0.6	-8.4	-
16	7	11	1	-5.8	0	-43
17	8	5	18	-20	-13	-14
18	3	4	8	-16	-17	-18
19	0	11	-	13	28	-
20	0	11	5	-19	-22	-32
21	-	-	-	-	-	-
22	4	3	17	-16	-16	-5.8
23	3	2	5	-13	-0.4	-1.5
24	5	5	6	-13	23	12
25	6	4	9	-2.5	-12	-8.5
26	3	5	9	-3.3	-1.3	-7.3
27	7	3	7	-12	-13	-35
28	-	-	-	-	-	-
29	4	1	1	10	-5.5	-55
30	2	4	-	-33	-29	-
31	5	2	8	-1.9	-11	-32
32	3	2	7	-7.5	-7.5	-8.8
33	112	34	6	14	-25	-40
34	18	10	-	-33	-35	-
35	8	8	8	6.8	13	30

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TABLE D-III. Test Irradiation - 170 keV Filtered X-Rays

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$					Bias as % of Dose				
	Dose in mrem					Dose in mrem				
	60	120	240	500	1000	60	120	240	500	1000
1	0	2	1	2	3	-78	-78	-79	-56	-56
2	100	0	56	3	4	-15	-33	-33	-56	-65
3	17	9	7	2	7	-45	-26	-21	-16	-13
4	8	4	3	14	7	-72	-71	-71	-64	-66
5	58	34	17	9	8	37	28	15	4.6	8.7
6	7	2	3	7	8	-22	-18	-15	-0.4	0.7
7	58	14	13	10	10	-12	10	4.6	60	49
8	67	22	27	24	72	417	258	171	122	110
9	17	16	12	11	8	33	19	7.9	-8.4	-17
10	17	0	15	10	14	65	34	29	13	9.5
11	17	16	8	5	9	-52	-44	-50	-50	-54
12	21	21	17	6	6	-32	-29	-27	-24	-24
13	-	-	-	-	-	-	-	-	-	-
14	19	28	13	15	14	-45	-44	-26	-24	-26
15	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-
19	5	5	6	8	7	-40	-39	-36	-36	-37
20	84	69	28	13	22	82	80	58	36	38
21	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-
23	17	10	5	9	6	-50	-42	-41	-40	-44
24	23	47	32	15	19	10	-7.5	-5.4	-0.6	-5.6
25	8	8	13	13	11	13	15	13	3.6	2.2
26	0	0	0	0	0	3.3	7.5	10	4.4	2.2
27	15	12	7	8	53	-20	-19	-15	-17	-27
28	-	-	-	-	-	-	-	-	-	-
29	19	8	7	8	7	-8.3	-5.8	-2.1	1.2	-0.7
30	10	0	5	6	8	-22	-8.3	-10	-6.8	-4.8
31	17	28	13	10	18	-5.0	-19	-15	-22	-25
32	7	10	8	5	7	10	4.2	0.8	-0.8	0.5
33	20	8	15	32	14	-13	3.3	19	14	12
34	0	92	7	3	1	102	100	79	48	31
35	0	0	0	20	13	58	-20	14	16	5.1

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TABLE IV. Test Irradiation - 100 keV Filtered X-Rays

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$					Bias as % of Dose				
	Dose in mrem					Dose in mrem				
	60	120	240	500	1000	60	120	240	500	1000
1	0	3	5	3	5	-60	-63	-19	-20	-23
2	623	0	10	40	5	133	-17	-23	-30	-56
3	17	0	5	2	1	-47	-25	-15	-18	-11
4	10	5	7	2	23	-47	-50	-46	-36	50
5	17	10	19	19	28	5.0	-4.2	-9.2	-9.4	-4.4
6	6	5	13	17	10	22	23	42	56	52
7	42	14	18	13	18	10	18	14	28	35
8	46	42	32	47	41	217	208	204	220	220
9	27	29	19	12	12	50	28	15	5.6	-8.5
10	0	34	35	31	23	117	117	88	76	61
11	10	22	12	17	12	-22	-17	-20	-22	-25
12	10	13	6	8	9	-13	-3.1	-5.4	-0.8	-6.1
13	-	-	-	-	-	-	-	-	-	-
14	50	44	41	24	25	22	38	34	36	32
15	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-
19	19	9	16	11	9	8.3	4.2	6.3	15	3.3
20	0	71	21	40	20	8.3	32	2.5	-9.6	-7.3
21	-	-	-	-	-	-	-	-	-	-
22	-	-	-	-	-	-	-	-	-	-
23	48	4	11	13	10	-5.0	-9.2	-5.4	-4.2	-14
24	52	65	85	55	107	43	16	38	72	68
25	24	34	16	30	0	68	78	71	64	60
26	0	0	0	0	0	0	0	0	2.0	0
27	24	17	14	142	23	-10	-4.2	-2.9	26	-1.8
28	-	-	-	-	-	-	-	-	-	-
29	32	30	38	10	25	63	67	79	80	140
30	8	12	16	22	102	32	46	58	64	38
31	17	17	15	8	17	22	4.2	-6.3	-12	-17
32	6	10	6	9	10	0	-4.2	0	1.0	3.3
33	50	26	24	20	17	17	31	41	50	41
34	0	0	6	21	12	217	300	163	158	89
35	0	0	0	20	9	-67	-58	-71	-66	-68

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TABLE D-V. Test Irradiation - 17 keV "K" Fluorescent X-Rays

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	60	120	240	60	120	240
1	3	2	0	-50	-56	-42
2	0	19	11	-50	-42	-67
3	0	0	4	0	-8.3	2.9
4	10	14	13	13	17	25
5	8	4	10	22	15	2.1
6	5	14	7	1.7	6.7	8.8
7	0	10	17	150	142	154
8	0	10	5	0	-7.5	-9.6
9	19	0	4	-42	-50	-50
10	37	16	13	40	3.3	-10
11	8	10	6	-15	-16	-26
12	0	5	4	58	57	58
13	-	-	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	6	3	2	-90	-92	-96
20	6	4	9	58	58	58
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	10	19	21	22	28	50
24	8	4	5	-10	-9.2	-5.4
25	10	8	6	30	15	7.1
26	0	0	0	25	25	25
27	8	0	0	32	25	25
28	-	-	-	-	-	-
29	17	9	3	-38	-44	-42
30	3	0	2	-47	-49	-50
31	-	-	-	-	-	-
32	50	8	47	105	117	88
33	8	135	10	73	125	63
34	-	-	-	-	-	-
35	-	-	-	-	-	-

TABLE D-VI. Test Irradiation - Beta Radiation

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	120	240	500	120	240	500
1	0	4	5	-33	-33	-36
2	25	11	11	-2.5	-3.8	-1.8
3	0	4	4	0	-1.7	-7.8
4	15	27	9	34	29	15
5	52	40	9	-13	-12	-22
6	5	3	5	-43	-36	-32
7	22	9	6	-13	-10	-11
8	110	13	170	58	125	84
9	19	9	7	-25	-31	-36
10	19	18	9	-25	-26	-28
11	20	6	6	-29	-31	-36
12	30	10	7	29	27	32
13	-	-	-	-	-	-
14	21	10	5	2.5	5.4	7.2
15	21	27	4	30	18	19
16	-	-	-	-	-	-
17	30	15	16	-8.3	-5.8	5.0
18	11	13	9	-19	-1.5	-1.6
19	28	9	13	18	18	26
20	8	75	4	-3.3	9.6	3.6
21	-	-	-	-	-	-
22	0	12	6	8.3	10	2.2
23	13	8	2	3.3	-1.7	-17
24	14	9	7	15	19	18
25	17	7	7	-13	-9.6	-7.6
26	5	11	5	-19	-9.6	-8.2
27	8	0	4	-6.7	-4.2	-11
28	-	-	-	-	-	-
29	10	12	3	21	16	14
30	0	3	5	-10	-7.9	-8.8
31	17	10	19	4.2	-10	-16
32	5	4	1	-32	-33	-34
33	14	7	8	-32	-33	-34
34	8	0	0	2.5	0	-4.0
35	10	8	8	-13	-17	-20

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TABLE D-VII. Test Irradiation - Radium Gamma Plus Beta - Radium Gamma Component

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	120	240	500	120	240	500
1	15	29	13	21	20	22
2	275	0	5	104	13	0
3	4	4	2	0.8	6.3	15
4	29	19	11	16	27	4.2
5	14	13	6	8.3	-1.3	-5.2
6	14	4	7	-18	-17	-14
7	16	9	11	-2.5	-2.1	7.6
8	13	5	7	-5.0	0.8	0.2
9	10	5	3	21	13	1.0
10	19	23	51	50	26	-4.8
11	13	2	5	38	-35	-40
12	12	10	6	13	13	10
13	-	-	-	-	-	-
14	0	12	7	-8.3	3.1	-0.6
15	0	3	0	17	7.9	4.0
16	-	-	-	-	-	-
17	16	22	8	-2.5	12	-1.6
18	-	-	-	-	-	-
19	16	11	7	28	27	30
20	31	13	8	0.8	16	20
21	21	3	3	-32	-25	-22
22	10	7	2	-4.2	-4.6	-7.0
23	4	6	3	-18	-14	-22
24	8	5	4	7.5	5.0	4.2
25	8	6	6	11	-1.7	-3.6
26	8	3	4	-2.5	-1.7	3.2
27	0	0	1	-4.2	-2.1	0.2
28	-	-	-	-	-	-
29	17	12	5	21	20	13
30	0	10	9	-13	-6.7	-4.8
31	0	6	5	17	5.8	-2.8
32	0	3	3	8.3	4.6	3.6
33	18	14	14	-33	-24	-2.2
34	0	0	4	-17	-17	-18
35	0	3	4	-21	-21	-14

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TABLE D-VIII. Test Irradiation - Radium Gamma Plus Beta - Beta Component

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	120	240	500	120	240	500
1	53	10	28	-28	-21	-40
2	8	12	23	-57	-58	-72
3	10	34	4	4.2	20	-0.6
4	29	16	12	33	11	26
5	31	42	21	25	10	15
6	7	7	16	-28	-20	-15
7	16	15	3	11	6.7	-14
8	65	40	11	192	188	162
9	0	12	13	-8.3	-23	-26
10	31	18	7	-51	-54	-52
11	8	7	5	-83	-88	-80
12	14	9	7	40	28	22
13	-	-	-	-	-	-
14	24	21	3	42	20	6.6
15	8	18	0	-23	12	0
16	-	-	-	-	-	-
17	18	18	13	-45	-54	-38
18	-	-	-	-	-	-
19	27	23	10	-33	-27	-34
20	24	16	12	0	-15	-36
21	47	7	28	18	0	-22
22	21	9	5	36	37	30
23	12	7	6	13	-22	-30
24	23	7	12	4.2	25	50
25	10	12	4	-21	-7.5	-20
26	13	9	8	-13	-9.2	-9.8
27	0	0	1	4.2	-8.3	-14
28	-	-	-	-	-	-
29	0	12	5	50	46	28
30	0	7	8	-18	-23	-42
31	21	11	7	28	2.1	-12
32	10	4	2	-13	-15	-17
33	8	8	27	12	12	11
34	17	3	4	4.2	0.4	-2.2
35	0	6	9	17	19	7.8

TABLE D-IX. *Test Irradiation - Radium Gamma Plus 17 keV X-ray -
Radium Gamma Component*

Processor Number	Relative Error			Bias as % of Dose		
	$\frac{2\sigma}{D} \times 100$			Dose in mrem		
	Dose in mrem			Dose in mrem		
	120	240	500	120	240	500
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	8	4	4	15	13	17
4	34	11	5	18	8.3	0.8
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	0	10	4	-17	-9.6	4.0
8	24	9	5	83	83	88
9	4	6	3	36	25	9.6
10	-	-	-	-	-	-
11	-	-	-	-	-	-
12	17	12	4	-0.8	4.6	-0.8
13	-	-	-	-	-	-
14	-	-	-	-	-	-
15	0	0	0	4.2	4.2	0
16	-	-	-	-	-	-
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	25	18	4	-37	-38	-30
20	13	20	4	-3.3	9.6	18
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	7	7	3	2	3	0
24	94	7	5	48	4.2	6.0
25	0	4	7	8.3	-3.3	-3.6
26	0	0	0	-8.3	-4.2	0
27	-	-	-	-	-	-
28	-	-	-	-	-	-
29	14	9	8	25	14	9.8
30	16	10	4	-22	-16	-7.4
31	8	2	2	11	2.1	-6.4
32	0	0	3	0	0	2.2
33	4	6	5	-36	-46	-50
34	0	4	15	-58	-23	-26
35	-	-	-	-	-	-

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TABLE D-X. Test Irradiation - Radium Gamma Plus 17 keV X-ray -
17 keV X-ray Component

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	120	240	500	120	240	500
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	0	4	2	17	-5.4	-40
4	89	6	6	17	-5.8	-26
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	19	0	21	140	130	150
8	71	72	265	1000	1125	640
9	-	-	-	-	-	-
10	-	-	-	-	-	-
11	-	-	-	-	-	-
12	8	9	8	51	58	40
13	-	-	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	2	2	2	-83	-83	-86
20	7	8	10	29	30	-2.2
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	5	6	4	-6.7	6.3	-3.2
25	5	6	8	6.7	-4.6	-20
26	0	0	0	13	6.3	-2.0
27	-	-	-	-	-	-
28	-	-	-	-	-	-
29	8	3	5	-48	-50	-56
30	2	3	3	-54	-58	-68
31	-	-	-	-	-	-
32	0	4	4	10	9.6	98
33	-	-	-	-	-	-
34	-	-	-	-	-	-
35	-	-	-	-	-	-

TABLE D-XI. *Test Irradiation - Radium Gamma Plus 17 keV X-ray -
Total Dose*

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	240	480	1000	240	480	1000
1	8	5	8	-42	-42	-21
2	0	18	2	-17	-35	-49
3	-	-	-	-	-	-
4	-	-	-	-	-	-
5	5	7	6	19	8.1	8.6
6	4	2	3	-29	-29	-32
7	-	-	-	-	-	-
8	-	-	-	-	-	-
9	-	-	-	-	-	-
10	10	6	31	-1.3	-10	-33
11	8	5	2	-28	-31	-44
12	-	-	-	-	-	-
13	-	-	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	-	-	-	-	-	-
20	-	-	-	-	-	-
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	-	-	-	-	-	-
25	-	-	-	-	-	-
26	-	-	-	-	-	-
27	0	0	0	6.3	2.1	-0.5
28	-	-	-	-	-	-
29	-	-	-	-	-	-
30	-	-	-	-	-	-
31	-	-	-	-	-	-
32	-	-	-	-	-	-
33	-	-	-	-	-	-
34	-	-	-	-	-	-
35	-	-	-	-	-	-

TABLE XII. Test Irradiation - Thermal Neutrons

Processor Number	Relative Error, $\frac{2\sigma}{D} \times 100$			Bias as % of Dose		
	Dose in mrem			Dose in mrem		
	60	120	382	60	120	382
1	225	245	0	17	18	-47
2	495	320	356	267	358	366
3	8	4	5	1.7	-0.8	-9.2
4	347	415	37	417	417	393
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	17	16	4	13	11	15
8	24	14	6	-8.3	0	2.1
9	215	122	14	633	467	419
10	420	527	203	550	500	524
11	174	145	83	617	558	628
12	8	16	10	52	44	39
13	-	-	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	-	-	-	-	-	-
20	68	20	13	83	92	42
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	-	-	-	-	-	-
24	-	-	-	-	-	-
25	0	0	0	25	-17	-15
26	-	-	-	-	-	-
27	-	-	-	-	-	-
28	-	-	-	-	-	-
29	19	21	22	-75	-82	-81
30	33	32	4	40	-3.3	-7.1
31	-	-	-	-	-	-
32	340	212	131	683	633	246
33	-	-	-	-	-	-
34	3447	122	414	1300	675	340
35	-	-	-	-	-	-

TABLE D-XIII. Test Irradiation - Fast Neutrons

Processor Number	Relative Error,			Bias as % of Dose		
	$\frac{2\sigma}{D} \times 100$			Dose in mrem		
	200	262	787	200	262	787
1	27	8	21	-93	-76	-66
2	448	348	105	220	99	-27
3	17	33	41	30	15	14
4	61	86	120	5.0	3.1	51
5	21	23	12	7.5	9.2	6.5
6	26	66	22	65	53	62
7	43	26	13	19	7.6	10
8	-	-	-	-	-	-
9	19	43	54	14	50	25
10	92	79	204	90	99	105
11	12	73	21	55	53	42
12	56	27	15	25	21	15
13	27	12	20	80	92	91
14	17	5	1	49	38	46
15	-	-	-	-	-	-
16	61	21	38	60	69	76
17	-	-	-	-	-	-
18	-	-	-	-	-	-
19	31	28	36	90	111	140
20	11	7	10	12	11	5.5
21	-	-	-	-	-	-
22	-	-	-	-	-	-
23	31	26	30	115	95	93
24	115	72	57	110	111	89
25	27	23	16	7.5	-5.7	18
26	22	25	13	32	28	23
27	12	15	74	41	38	29
28	-	-	-	-	-	-
29	25	51	39	80	92	80
30	7	12	6	-75	-73	-72
31	59	46	31	145	156	152
32	33	55	70	80	61	20
33	16	23	13	-1.0	14	-1.9
34	124	315	193	-47	31	12
35	-	-	-	-	-	-

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