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Interim Status Report of the TMI Personnel Dosimetry Project

Bryce L. Rich
Joseph L. Alvarez
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June 1981

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ABSTRACT

The current 2-chip TLD personnel dosimeter in use at Three Mile Island (TMI) has been shown inadequate for the anticipated high beta/gamma fields during TMI recovery operations in some areas. This project surveyed the available dosimeter systems, set up an Idaho National Engineering Laboratory (INEL) prototype system, and compared this system with those commercial systems that could be made immediately available for comparison. Of the systems tested, the new INEL personnel dosimeter was found to produce the most accurate results for use in recovery operations at Three Mile Island Unit-2 (TMI-2), where personnel exposure to high-level, high-energy, mixed-fission-product radiation fields is probable. The other multiple-chip or multiple-filter systems were found less desirable at present, due to one or more of the following reasons: (a) need to modify the badge design, (b) need to change or develop the calculation techniques, (c) need to complete or verify the calibration and performance, (d) non-competitive cost, and (e) not immediately available.

The most prominent deficiency in the INEL dosimeter stems from the fact that it is a developing system and lacks a completely automated reader, thus requiring increased dosimeter handling. In addition, the x-ray and thermal neutron responses of the INEL dosimeter require additional development in order to obtain the desired degree of accuracy. Although a semiautomated system is currently available, increased handling in comparison with fully automated systems is still necessary. However, the RESL estimates that a automated prototype reader system will be in operation by the end of CY-1981.

Three alternatives for operational dosimetry are discussed. Based upon such factors as technical adequacy, low capital outlay, and speedy availability a combination of a modified version of the presently used Harshaw 2-chip dosimeter and the INEL dosimeter is recommended. The

suggested modification of the Harshaw 2-chip system would be automatic and should be capable of producing high-quality gamma dosimetry, while the INEL dosimeter would provide accurate beta dosimetry.

The state of the art of personnel dosimetry is changing rapidly and will be affected by the soon-to-be-released ANSI standard N13.11 and subsequent NRC guides. It is therefore recommended that acquisition of expensive automated systems be deferred unless the supplier can demonstrate badges of adequate design. In any case, procurement of a fully automated system should be preceded by demonstrated performance relative to the ANSI N13.11 Standard and to the special conditions to be encountered during TMI recovery.

SUMMARY

The accident at TMI-2 released large quantities of fission products into areas where personnel are required to enter. The Harshaw 2-chip dosimeter in use at TMI, and typical of those used in the nuclear power industry, has only a 270 mg/cm^2 filter over the "penetrating" detector and is inadequate to measure the doses from the high-energy, high-level, beta-gamma radiation fields. Though there are beta dosimeters in use in the nuclear industry that could give improved response, beta dosimeters in general are not well developed for providing nonpenetrating versus penetrating dose. The most directly related, and applicable personnel dosimeter experience is associated with protection programs at chemical processing plants where personnel exposure to fission product spills are a part of the health physics experience.

It was determined that upgrading the TMI personnel dosimetry to state-of-the-art levels would require little effort above that required for minimum upgrading. The objective of this project was to identify the most applicable dosimeter system immediately available and provide technical support in placing an upgraded system into service.

The new INEL dosimeter had been specifically designed to measure the dose from radiation fields typical of those at TMI. Since published INEL response data were good and a Harshaw hot gas reader, which is compatible with the INEL dosimeter system, had been previously purchased by GPU and was in place at TMI, the decision was made to set up and calibrate a prototype INEL system, using borrowed TLD dosimeters, badges, and miscellaneous equipment. It was planned to perform a direct comparison with other immediately available systems, thereby providing supporting data required to ensure that a superior system was available for recovery operations. Data from the Harshaw 2-chip system in use at TMI was included in the comparison to document the degree of improvement possible through use of an improved system.

The calibrations and comparisons utilized various combinations of 0.662 Mev gamma radiation from Cs-137, and beta radiation from 0.766 Mev (theoretical) Tl-204 and 0.546/2.27 Mev (theoretical) Sr/Y-90. The INEL badge produced the most accurate response of those evaluated. Angular response improvement, the promise of future neutron and emergency monitoring capability, and minimal cost are additional strong points of the INEL system. However, it is recognized that the other multifilter systems can probably be improved by changing the badge design (with careful attention to filter materials and effects) and carefully calibrating and developing dose evaluation[a] techniques. The INEL system has not been fully automated, and when compared to more automated systems will require more care in handling the badge and components, which is an operational inconvenience.

During the continuing development and testing[b] of the new, prototype INEL dosimeter, very recent data--since the completion of the original draft of this report--have indicated that it overresponds to x-ray radiation in the range of 15 to 100 keV by an amount larger than anticipated, and also overresponds to thermal neutrons alone. The dosimeter currently in use (the "old" dosimeter) at the INEL, which employs 540 mg/cm^2 of aluminum and 100 mg/cm^2 of plastic filtration on the penetrating chip, was found to have excellent response throughout the x-ray and gamma-ray region. These data indicated that the new INEL dosimeter should not be unequivocally recommended as total replacement for the system now in use at TMI. The excellent (but fortuitious) response of the "old" INEL dosimeter to x-rays suggests that the 2-chip Harshaw system currently

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a. The objective of this project was not to develop a new badge. Under the time constraint set for this evaluation, the Panasonic, the Harshaw 2-chip, and a film badge were compared just as they were supplied--not modified in any way. The Harshaw 4-chip system and other comparable badges were not immediately available, which fact restricted the number of comparisons.

b. Testing continues in response to the requirements of the current draft of the proposed ANSI N13.11 standard requirements which is nearing completion and promises to have a large impact on dosimetry systems in service.

in use at TMI could be easily modified by adding filtration equivalent to the "old" INEL system and thus provide a dosimeter with "ideal" gamma/x-ray response. It should be emphasized that the modified 2-chip badge would still be an inadequate beta dosimeter in a mixed or unknown field.

Although the ideal personnel dosimeter for beta response in mixed beta-gamma fields does not exist, the INEL dosimeter design appears to represent the technical state of the art for high-level beta fields and is the recommended dosimeter for TMI recovery operations. It should be used to supplement the modified Harshaw-two-chip system. Operational convenience through more completely automated readers and data processing could justify choice of another system eventually. However, such choice should be made only after careful evaluation of the practicality of modification and of the acceptability of response to a calibration matrix equivalent to that used in this project.

As a support to the project, new instrumentation was developed for characterization of the sources used in the calibration of the personnel dosimeters. The dose rate, versus distance and plastic absorber thickness, was measured. In addition, the average and maximum energy, versus distance and absorber thickness, were measured.

A calibration and operating procedure was developed for operating the INEL system. This section of the report will be of value should the INEL system be used at TMI.

ACKNOWLEDGMENTS

EG&G Idaho accepted the responsibility to provide the Technical Integration Office (TIO) technical coordination and direction in the evaluation of personnel dosimetry systems, and to recommend the best system currently available for implementation in the TMI-2 recovery operations. Several groups have contributed technical expertise, equipment, and manpower.

S. Schofield and P. Wildenborg spent several weeks at TMI directing the set up and calibration of the INEL prototype system. Their technical and organizational strengths gave foundation to the project. J. Hoggan worked intimately, both at Idaho and TMI, as a member of the team that developed the dose rate and spectrometer systems. His technical skills were also key to completion of the project to this point in time. G. Eidam and the TIO staff were most helpful in providing on-site coordination and all support requested. O. Pack should be especially recognized for the pleasant manner and skill with which he edited the text without disturbing the technical content.

DOE Radiological and Environmental Sciences Laboratory (RESL)

D. E. Jones, O. Parker, and P. Boren designed the INEL badge, and V. P. Gupta and D. Parker designed the associated equipment. This team is responsible for the INEL system. The team members, together with J. P. Cusimano and R. Storm, have been free with advice, technical reviews, and ready assistance in every phase of the project. TLDs, badges, decappers, technical specifications for equipment purchase, etc., were provided on request with an enthusiasm that invited use of their service. Their service was a key to the success of this project.

T. Gesell, a consultant from the University of Texas at Houston working under the direction of D. Jones of RESL, spent several summers developing the INEL beta dosimetry method and algorithms, and coauthored report IDO-12090. He was available as a consultant to this project and contributed by guiding the technical development and offering advice and assistance as needed.

Exxon - ICPP

G. Mansfield and R. Ficke, professional HPs at the Idaho Chemical Processing Plant (ICPP), spent many weeks at TMI contributing expertise gained from their chemical processing plant experience in addition to their basic professional and organizational strengths in guiding the development effort and contributing to the text of the report.

General Public Utilities

P. Ruhter, J. Hildebrand, H. Peterson, and D. Shriner, professional HPs at TMI, by their technical understanding, enthusiasm, and active participation, contributed more than adminstrative support in encouraging completion of this project.

Porter Consultants, Inc.

S. Sherbini and S. Porter, performed many technical experiments, analyses, and evaluations that were useful in arriving at our conclusions. Work was done with the radiation fields, the response of the Harshaw badges, and other personnel dosimeter systems, as well as with the INEL dosimeter.

Nuclear Science Services

R. Biskey and the personnel dosimetry technicians were extremely helpful, enthusiastic, and capable in their support of every phase of the project. Administrative and technical delays were routinely minimized by Mr. Biskey who assisted in keeping the project on track with a minimum of delay.

Radiation Services

R. Jacobs, J. Bradshaw, M. Pavelek, O. Burkhart, and the other instrument maintenance staff members were most helpful in providing facilities, assistance in the use of the sources, and technical support as needed in keeping the project on schedule.

DEFINITIONS AND ASSUMPTIONS

Key terms and assumptions used in this report are defined in this section.

1. Skin dose has been defined traditionally as the dose occuring at 7 mg/cm^2. The International Committee on Radiological Protection (ICRP) and this report define the skin dose as the dose in the range of 5 to 10 mg/cm^2. This corresponds to an average of 7 mg/cm^2 and is thus essentially the same, except for extremely weak β particles. This quantity is referred to as shallow dose in the ANSI N13.11 draft standard.

2. Dose to various organs from different types of radiation can result in confusing terms. Beta radiation is generally considered <u>nonpenetrating</u> or a potential <u>skin dose</u> problem only. However, high-energy betas can be more penetrating in some instances than low energy x-rays. In addition, skin dose is a sum of both the beta or nonpenetrating and the gamma or penetrating radiation, since the gamma component is typically subtracted from the open window chip in making the nonpenetrating component determination. In this report, we will use the term <u>penetrating</u> to represent gamma, and any other radiation that penetrates to a depth of 1000 mg/cm^2 in tissue. <u>Nonpenetrating</u> will refer to beta or other radiation that results in a dose to tissue at 5 to 10 mg/cm^2 but not to 1000 mg/cm^2. The dose at 1000 mg/cm^2 is referred to as deep dose in the ANSI N13.11 draft standard.

3. All dose rate values listed in this report are dose rate in tissue values.

4. The basic development of the design and theory of the INEL dosimeter was done by D. Jones, V. Gupta, F. Kalbeitzer, J. Cusimano, and T. Gesell at the INEL. The objective of this

project at TMI was to implement an established system, not to perform original development work, though further analyses and verifications were performed at TMI as a function of calibrating the system and determining the operating characteristics. Since the theory is adequately defined in IDO-12090, it will not be repeated in this report.

5. The development of the algorithm for obtaining dose from the dosimeter data was also presented in IDO-12090, and will not be repeated in this report. The algorithm will be presented in the section describing the calibration and operating procedures, without the development details.

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FIGURES

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INTRODUCTION

TLD Beta Dosimetry Discussion

The purpose of personnel dosimetry is to derive from physical measurements of the radiation environment information regarding the quantity of energy deposited per unit mass of tissue, i.e., the radiation dose. Of primary interest in beta dosimetry is the dose to the first 5 to 10 mg/cm^2 of tissue (the "skin" dose), and the dose to the lens of the eye.[1] Since the eyes will usually be protected from beta radiation by respirator masks or safety glasses, the skin dose is the principal concern in most situations.

The most common detectors used in current personnel dosimeters are LiF thermoluminescent dosimeters (TLDs), although photographic film detectors are still in use also. The integrated light output of TLDs is proportional to the total energy deposition (dose) throughout the chip. Since the effective atomic number of lithium fluoride is close to that of tissue,[2,3] the light output of the chip can be directly related to tissue dose except at x-ray energies, where LiF exhibits a small overresponse.

As seen in the upper sketch of Figure 1, the rate of energy deposition for gamma rays passing though the body of the chip (approximately 240 mg/cm^2) is fairly constant (charged particle equilibrium). Thus, the average dose is essentially equal to the dose at any point along the thickness of the chip, and the average dose as derived from the chip is equal to the skin dose between 5 and 10 mg/cm^2. As seen in the lower sketch of the figure, beta radiation will be significantly attenuated as it passes through the body of the chip. The initial rate of energy deposition will be higher than the average rate of energy deposition. Thus, the light output recorded by the reader will indicate an average beta dose for the total chip thickness, which will be lower than the skin dose received at 5 to 10 mg/cm^2.

This underresponse of the dosimeter must be corrected by a beta correction or "calibration" factor. As might be expected, the amount of

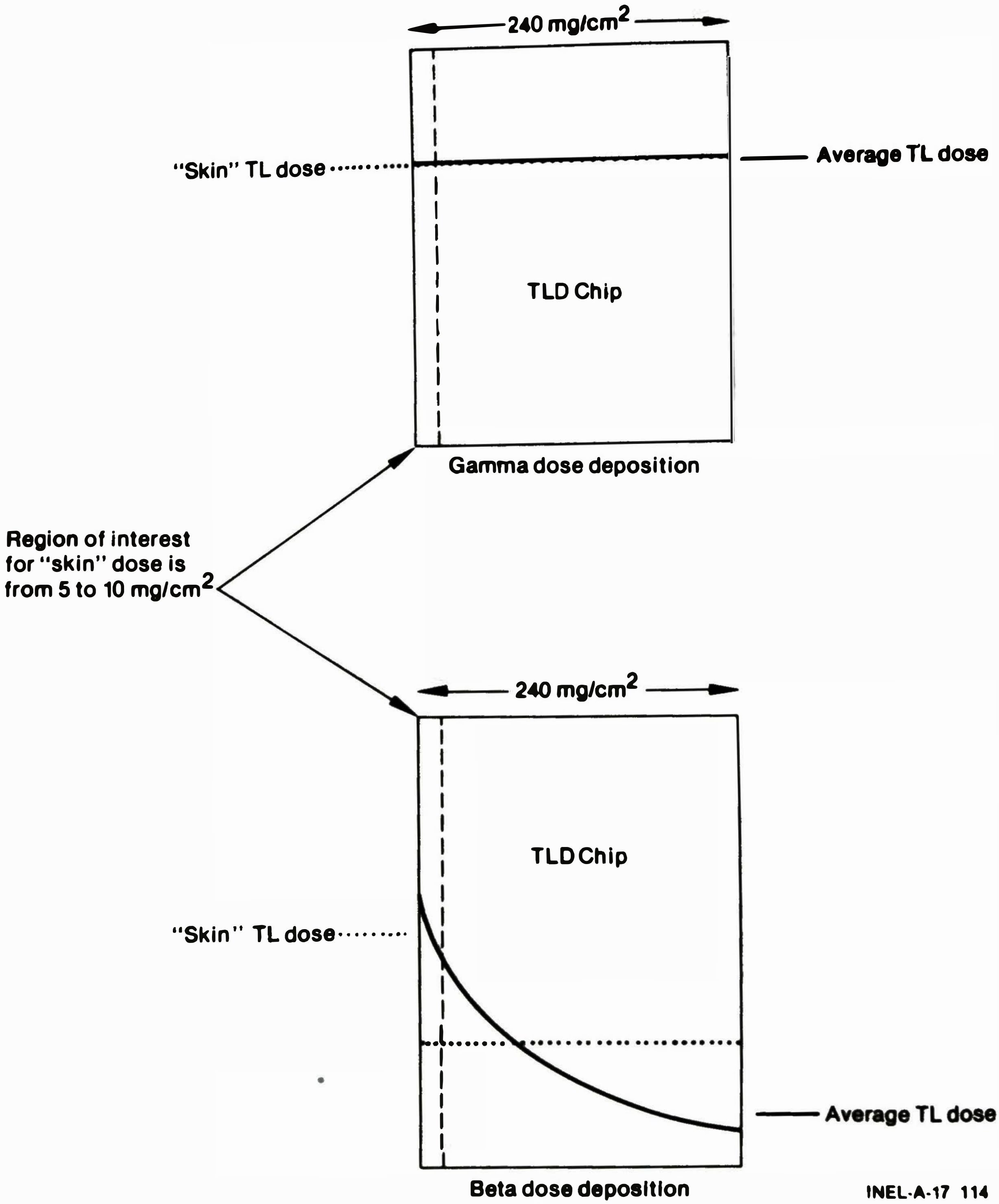

Figure 1. Beta dose deposition.

attenuation within the chip, and therefore the correction factor, depends upon the effective energy of the beta spectrum. A "harder" or higher energy beta spectrum would be expected to require a smaller correction factor, since the higher energy betas will be attenuated less than will betas of lower energy. The beta correction factor will vary from situation to situation, depending upon the isotopic mix of the source, distance from the source, and amount of absorbing material between the source and the dosimeter.

The most common dosimetry techniques for measuring personnel beta radiation dose at the present time can be categorized into three systems as follows:

1. The 2-chip system, utilizing 240 mg/cm^2 thick LiF chips under two different absorbers - The thin absorber is generally intended to approximate a skin thickness (5-10 mg/cm^2) but due to problems of construction is usually thicker (10 to 50 mg/cm^2). The second absorber is also variable and in different badges ranges from approximately 250 mg/cm^2 (approximating the depth of the lens of the eye) to 1000 mg/cm^2 (approximating the depth of other critical organs of the body). One of these common designs is in use at TMI and utilizes a 30 mg/cm^2 "thin" paper and plastic absorber and a 270 mg/cm^2 "thick" aluminum and plastic absorber. This 2-chip badge design prevents beta particles under approximately 0.2 Mev from penetrating to the "open window" or "nonpenetrating" chip, and allows betas over approximately 0.75 Mev to penetrate to the "penetrating" chip (see Figure 2).

   Though the badge responds reproducibly (see Table 1), the 270 mg/cm^2 gamma shield allows approximately 20-30% Sr/Y-90 beta penetration. The problem, however, lies not only in the penetration but in the fact that the betas have different calibration factors, based on their energies, in the thick chips. For example, the beta-calibration factor is approximately 2 for Sr/Y-90 and 4 for uranium (which is used as the routine

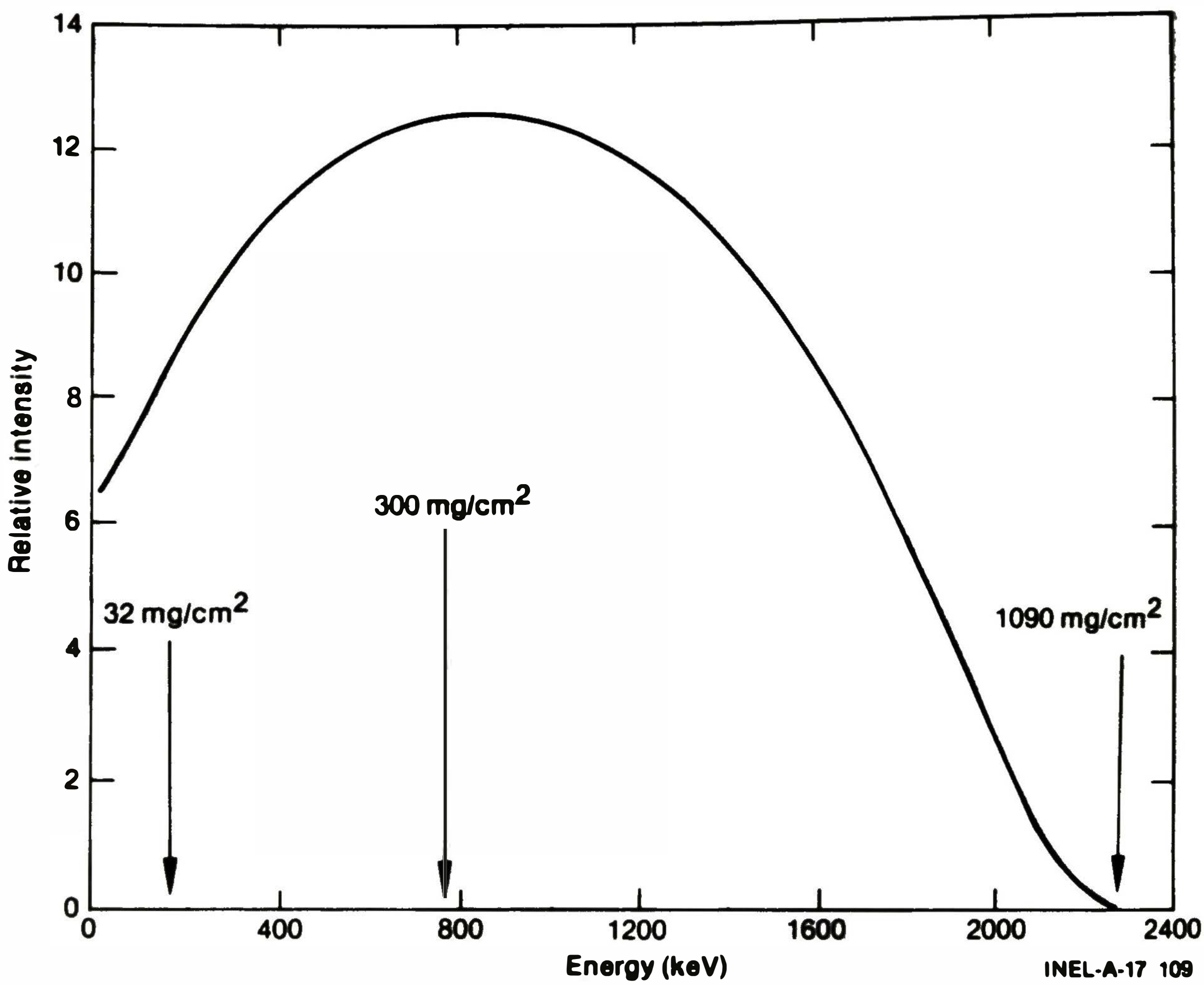

Figure 2. Y-90 beta energy spectrum.

TABLE 1. RESPONSE OF THE TMI 2-CHIP TLD PERSONNEL DOSIMETER TO CALIBRATED SOURCES AT AN INDEPENDENT NATIONAL LABORATORY

	Gamma (Cesium-137)		Beta (Strontium-90)	
Badge No.	Given[a] (rem)	Reported (rem)	Given[a] (rem)	Reported[b] (rem)
1	0	0.021	0	0
2	0	0.082	0.27	0.482
3	0	0.073	0.27	0.548
4	0	0.535	2.7	5.0
5	0	0.589	2.7	5.1
6	0	4.16	27.0	59.3
7	0	5.17	27.0	50.6
8	0	51.44	270.0	589.8
9	0	43.3	270.0	566.4
10	0.27	0.343	0.27	0.358
11	0.27	0.344	0.27	0.155
12	0.27	0.318	0.27	0.377
13	2.7	2.63	0.27	0
14	2.7	2.65	0.27	0
15	2.7	2.72	0.27	0
16	0.27	0.823	2.7	5.0
17	0.27	0.811	2.7	5.23
18	2.7	3.13	2.7	3.2
19	2.7	2.88	2.7	3.2
20	2.7	3.25	2.7	2.7
21	0.27	5.4	27.0	45.4
22	0.27	4.66	27.0	48.96
23	0.27	6.0	27.0	48.2
24	2.7	7.27	27.0	40.3
25	2.7	6.98	27.0	57.9
26	2.7	8.15	27.0	47.6
27	2.7	54.0	270.0	589.2
28	2.7	55.63	270.0	584.1
29	2.7	46.35	270.0	564.0

a. Data provided by NRC.

b. Data converted to dose using a "standard" uranium calibration.

calibration source). This results in a reported dose that is high by a factor of 2, when Sr/Y exposure is converted by a uranium calibration factor. A simple calibration test (simple because only one gamma ray and betas from one isotope plus daughter were used) with Cs-137 gammas and Sr/Y-90 betas (see Table 1) illustrates the inaccuracies which occur as a result of determining personnel dose using a dosimeter of this design in mixed beta-gamma fields. If the beta spectra are unknown and a single conversion factor (uranium for example) is applied, the badge results are questionable at best.

The theory behind the design of the 2-chip system with the 270 mg/cm^2 absorber on the penetrating chip is that it represents the approximate depth of the lens of the eye. As described above, the conversion of TLD-chip reading to absorbed dose requires a knowledge of the beta spectrum delivering the dose, and the reading of the chip under the 270 mg/cm^2 shield gives no indication as to what fraction of the reading was due to penetrating gammas or high-energy betas with calibration factors approximating 1, and what fraction resulted from lower-energy betas with calibration factors of 4 or more.

Obviously, this 2-chip design has severe limitations for routine use but more particularily is inadequate for TMI recovery service without additional field data on the composition of the radiation fields. However, it is commonly used in the industry, and is still in service in many commercial nuclear power facilities. Routine use will result in recording both penetrating and nonpenetrating, doses different than actual when high energy beta radiation is present. If converted by a uranium calibration factor, the reported nonpenetrating dose will probably be conservative (see Tables 1 and 6). This "conservative" position is not predictable or reliable. Choice of a high-energy beta calibration factor such as from Sr/Y-90 could result in a non conservative situation when the skin dose is or should be the limiting consideration. The TMI accident produced high-level, high-energy radiation fields from mixed fission product spills in which the high-energy beta component was up to 100 times the gamma component.[4] These fields resulted in conditions in which the skin dose was clearly limiting. But more important, the actual dose to either skin or deep organs cannot be determined to the desired degree of accuracy with the 2-chip dosimeter in use. The problem of beta radiation falsely elevating the measured penetrating dose can be overcome by using a thicker filter over the penetrating chip. The beta inaccuracies are not affected by this modification, however, and are inherent in a single thick-chip measurement.

2. The multiple filter/LiF chip system - The intent of the design of this system is to utilize data from the detectors under different filters and calculate an individual effective energy of the beta radiation. This allows the determination of an average calibration factor for each measurement such that the uncertainties in converting TLD readings to dose are reduced. This concept allows a much improved dose estimate to be made, as well as providing some information concerning the quality of the measured fields. However, the inherent thickness of the TLD chips, structural limitations of the badge, and uncertainties of applying a single average or effective energy to complex spectra result in limitations in the multiple filter badge design also. For example, when the beta component of the radiation field is less than the gamma component, the difference in the penetrating and nonpenetrating chip readings is small in relation to the reading on either chip, and hence is subject to definite sensitivity and accuracy limitations. Use of thick chips ($>5-10\ mg/cm^2$) also introduces an "averaging" effect that reduces the sensitivity of detection.

With all of its limitations, the multiple filter system utilizing LiF chips appears to represent the state of the art in personnel dosimetry in service at present. The system requires extensive calibration and response evaluation in order to properly utilize the data provided. The new INEL dosimeter is representative of this dosimetric approach.

3. The multiple filter/"thin" detector system - The availability of thin detectors (5-10 mg/cm^2) would provide a method of reducing inaccuracies introduced as a result of variable calibration factors in thick chips from a variety of beta energies. If the thin detectors had a "flat" energy response, they would theoretically measure dose directly at various depths in tissue as represented by different filter thicknesses in the badge. Various attempts have been made to produce thin detectors, ranging through LiF impregnated teflon, TLD powders, and surface Boron drifted LiF.

The Panasonic system utilizes "thin" (15 mg/cm^2) powders of $Li_2B_4O_7$:Cu and/or $CaSO_4$:Tm in badges with filters of varying thicknesses. Preliminary calibrations of the detectors with various gamma and X-ray sources[5] indicate the lack of a "flat" energy response. Theoretically, the thin detectors should be superior to the thick detector, however, the gamma/X-ray energy response variability characteristic requires a badge design compensation for mixed beta-gamma fields. A beta response calibration with filter optimization for beta-gamma response has not been performed on this system as of the date of this report, nor has the required badge modification been calibrated for x-ray response.

As will be discussed in the Calibration and Testing Results section, this type of dosimeter system has not been developed sufficiently at present to provide satisfactory response when compared to the LiF chip multi-filter system in high beta fields, which has relatively thick chips and is essentially energy independent. It is anticipated that with further evaluation and development (such as modifying the filters and algorithms in the Panasonic system) a thin detector system could provide superior performance.

Project Approach

Although the nuclear industry has been monitoring personnel dose in beta-gamma fields for many years, beta dosimetry techniques have not been thoroughly developed. As discussed in the previous section, the current "best" system has significant limitations. The facts (a) that permissible skin dose has been three to six times the permissible penetrating dose, and (b) that few fields exceed a three to one β/γ ratio in most facilities, have resulted in relegating this problem to a low priority and has led to oversimplification and sometimes overconservative monitoring procedures. Multiplying the recorded gamma dose by a factor based on field surveys--to obtain an estimate of the beta or skin dose without actually measuring this component of the dose--is an example of such an oversimplifying and conservative procedure. These conservatisms can cause inaccuracies and nonproductive personnel dose, primarily as a result of an increase in the transit time (increased number of trips) to and from the job in the radiation area.

Exposures in excess of regulatory guidelines at TMI highlighted the deficiency of the dosimeter used at TMI in particular, and the state-of-the-art deficiency within the nuclear industry in general. Since it was apparent that the TMI dosimeter results of these exposures were not accurate, GPU and its technical contractors initiated dosimetric studies primarily aimed at establishing the actual personnel doses. EG&G, under contract to the NRC, performed a technical evaluation of the exposure report. The results of all these studies emphasize the need for upgrading the beta dosimetry at TMI.[a]

The most applicable experience within the nuclear industry upon which to draw was associated with the operation of chemical processing facilities

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a. The standard Harshaw 2-chip dosimeter was included in this study to (a) document the magnitude of the expected improvement, (b) emphasize that this badge is the standard type used at many NRC-licensed facilities, and (c) document the response characteristics and magnitude of the inaccuracies for the record.

where high-level fission product spills were periodically encountered. This type of experience at the Idaho Chemical Processing Plant prompted the development of an improved personnel dosimeter by D. Jones et al of the Radiological and Environmental Services Laboratory, specifically designed to record a mixed beta-gamma field dose. In developing this dosimeter (the new INEL Badge), Gesell et al[6,7,10] related a ratio of two readings under different absorber thicknesses to a theoretical exponential attenuation coefficient. Having once established an effective attenuation coefficient, they derived a beta correction factor by taking the ratio of the integrated dose between 5 and 10 mg/cm^2, and the integrated dose between the back of any absorber and the back of the corresponding chip (e.g., absorber thickness plus 240 mg/cm^2). Such a ratio is equal to the underresponse and its inverse becomes the beta correction factor to be applied to the response of the chip under the thin window.

This dosimeter is being evaluated at the INEL, and preparations are in progress to implement its use at the INEL contractor facilities. Since an improved dosimeter was needed at TMI, due to the recovery operation in progress in the auxilliary building and the imminent containment building reentries and recovery operations, a major effort was needed that would draw on industry experience and provide the best available system on an as-soon-as-possible basis. EG&G, the TIO and INEL facilities contractor, was requested to coordinate and direct the effort to identify and implement an improved state-of-the-art personnel dosimeter system at TMI. In addition to the DOE-TIO objective of immediately obtaining a "best" system, recommendation was made to develop options and possibilities to upgrade personnel dosimetry technology in general. With this general background in mind, the project was accepted.

At the beginning of the project, a review of personnel dosimetry systems was performed in an effort to identify the most readily available dosimeters that offered the greatest probability of correct response to the mixed beta-gamma fields at TMI. A decision was made to place a prototype INEL dosimeter in service at TMI as soon as possible, for the following reasons:

- Of the systems considered[a], the INEL dosimeter appeared more specifically designed for beta dosimetry, and published reports promised superior response prospects

- A Harshaw hot-gas reader, which is compatible with the INEL system, had been previously purchased by GPU and though it was not calibrated was on site

- The system could be completed in a minimum of time by borrowing available badges, TLDs, and miscellaneous equipment from RESL at the INEL

- Professional personnel at the INEL were basically familiar with the design and could be available on a rotating basis to provide continuous support at TMI during set up, calibration, and comparison activities

- The INEL badge would be available on a limited basis for use by reentry team members within a few weeks

- Dosimeters at other DOE facilities offered no unique design capability and were less available in a short time

- The Harshaw 4-chip system (another multiple filter, LiF chip system) was not available until the initial investigation reported herein was being completed

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a. The literature search section of IDO 12090 was used as a starting point for the survey undertaken in this study.

- The Panasonic system[a] (a multiple filter, thin-detector system) had not been specifically designed nor calibrated for this service, and preliminary data by GPU were not encouraging.

Dr. T. F. Gesell (University of Texas) was retained as a consultant to the project, due to his expertise with the INEL system and dosimetry in general, having spent summers evaluating the dosimeter response and coauthoring IDO-12090, "A Personnel Beta Dosimetry Method for Reducing Energy Dependence." He assisted by outlining calibration procedures, evaluating results, and providing general technical support as requested.

As the INEL dosimeter was being placed in service and a detailed operating and response calibration completed, the dosimeter was used as one of three different badges worn by reentry team members. The data (Tables 3 and 4) constituted one phase of the intercalibration response study. In addition, four available dosimeters, which included a film dosimeter[b] in addition to the original three, were chosen for a response comparison study, using calibrated beta and gamma sources at TMI. It was anticipated that the technical response of the badges, coupled with other considerations of cost and convenience, would provide the data necessary to assist in the choice of at least an interim replacement TMI personnel dosimeter.

A draft of this report was generated ahead of schedule in order to supply additional data and recommendations to GPU to be used in the decision concerning a replacement of the two-chip system. Consequently, these results are reported in preliminary form, realizing that additional studies are necessary to fully explore the options.

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a. As stated at the outset, it is anticipated that with judicious change in dosimetry design (filter changes, for example) and careful calibration and evaluation, these dosimeter systems could respond competitively.

b. A film dosimeter was chosen due to availability and to establish film dosimeter response under these conditions.

DOSIMETRY SYSTEM CHOICE

Preliminary Choice - INEL Dosimeter

As previously stated, the INEL dosimeter was placed in service as the preliminary choice on the basis of being the one with the potential for the best technical response to mixed beta-gamma fields. Published response characteristics and the specific design for the intended service led to the anticipation of superior performance. In addition, the dosimeter badge fabrication incorporates boron into the molding plastic such that with successful development it can be used as an albedo personnel neutron dosimeter. Both TMI-1 and -2 use the same personnel dosimetry service, so neutron detection capability in the same badge would be a decided advantage. The badge design also provides for emergency and criticality dosimetry detectors and foils. The third design characteristic that argued for the INEL dosimeter was the attempt to minimize angular response.

The major disadvantage of the INEL system is that the reader is not yet automated and hence currently requires more handling of the badge components and closer control of the reading process. An additional Harshaw hot gas reader has been purchased and a modification produced to provide semiautomatic capability on both readers. A fully automatic system will not be available for some time, though a prototype system is under design and construction at RESL with completion estimated in CY-1981.

Another uncertainty associated with the INEL System is the fact that it is a newly developed concept and has not been field tested extensively. In fact, both x-ray and thermal neutron overresponses are presently being investigated at the INEL. However, extensive laboratory analyses and evaluations were completed during the past summer at the INEL, and as part of the project verifying the system accuracy for TMI field application.

For these reasons, it was decided to place the INEL System in service as a prototype dosimeter, calibrate and reestablish the response characteristics, and perform comparisons with other possible dosimeter choices, completing these evaluations in 3 to 4 months. It was felt that this course of action would provide the needed upgrade with minimum delay, while verifying that the final choice is the "best available" for this application. It was estimated that a complete working system could be in service within six months.

The dosimeters under consideration for this project are briefly described below:

The INEL Badge (previously discussed) prototype system has been calibrated and was operating at TMI as a result of three months effort by the EG&G coordinated team.

The Harshaw 2-Chip System was in service at the time of the accident and remains in routine service. Table 1 in the Introduction highlights the inherent inaccuracies of this dosimeter without modification for the intended TMI service.

The Panasonic System is in service as an environmental dosimeter, but has not been specifically calibrated for high-level mixed beta-gamma fields. Though it is assumed that the dosimeter could be modified and calibrated, resulting in improved response, the effort would require considerable effort. The dosimeter was simply compared as it exists today as a commercial environmental system.

The Landauer Film Dosimeter was compared as an available commercial personnel dosimeter service currently used at many facilities. It was compared as an example of a film dosimeter instead of TLD and as an example of a readily available system.

Other Dosimeters: The Harshaw 4-chip system became available during the week this report was being prepared. Though it is assumed that with careful calibration and evaluation the dosimeter would respond comparably, it was not available when necessary for the comparison.

There are many other dosimeters in service at various nuclear facilities, particularly at the DOE National Laboratories, which have been designed to record "penetrating" and "nonpenetrating" doses. However, the designs of the dosimeters of which we are aware had been studied and did not offer significant advantage or uniqueness expected to provide improved response and were less "available," due to the specific design and construction for their unique application.

Calibration and Testing Results

The calibration of the prototype INEL System at TMI involved a large number of exposures to the newly acquired and NBS-calibrated sources[8] at TMI (see the calibration matrix in Appendix B), and was performed to establish the operating parameters and characteristics of the reader and to verify the response characteristics of the dosimeter. The dosimeter response characteristics are listed and discussed briefly below:

Energy Response - Table 2 summarizes the energy response of the INEL dosimeter as determined at the INEL to a wider range of sources (energies) than available at TMI. The sources at the INEL and TMI are mounted differently and thus would be expected to produce different spectra. However, data gathered from exposures to Sr-Y and Tl sources verify the INEL response data very well. (Table 2 can be compared with Table 5 which appears near the end of this section.) The INEL badge measures penetrating or gamma exposure with a 10% accuracy in a variety of mixed beta-gamma fields. The measurement accuracy for beta exposure in the same fields is 10% for high energy (1.0 Mev); 30% over response for 0.7 Mev range; and 80% under response as the energy drops to 0.2 Mev or the cut off energy. As will be discussed further in Appendix C, this response does not represent an ideal, but is superior to the response of other available dosimeters.

Dose and Sensitivity Response - Determination of the beta dose depends upon subtraction of the reading on the penetrating (pen) TLD from the nonpenetrating (nonpen) TLD. Therefore, detection of small nonpen

TABLE 2. ABSOLUTE RESPONSE OF THE PROPOSED INEL DOSIMETER
(The indicated errors are two standard deviations of the mean.)

Isotope	E_{max} (MeV)[b]	Ratio of Observed to Delivered Beta Dose
Pm-147	0.225	0.29 ± .11
Tc-99	0.295	0.54 ± .05
Tl-204	0.764	1.35 ± .05
SrY-90 (Point)	0.546/2.26	1.05 ± .04
SrY-90	0.546/2.26	1.29 ± .04
CePr-144	0.31/2.98	0.98 ± .02

a. The delivered doses were based upon the calibrations adjusted for the average dose delivered between 5 and 10 mg/cm^2. This procedure was necessary because the INEL dosimeter is designed to measure the dose between 5 and 10 mg/cm^2, not the surface dose.

b. Theoretical Maximum Beta energies are reported here. As indicated in Appendix A, the average energies and actual maximum energies are quite different in a given source, depending on mounting technique.

components in a large pen field becomes statistically inaccurate. In addition, there is a definite energy cut off, which is a function of the absorber thickness of the filters and TLDs, making measurements below 0.2 Mev statistically inaccurate. For these conditions (β/r ratios <1 and maximum β energies in the 0.2 Mev range), doses of a few hundred mrad should probably be considered the limit of sensitivity. However, as the data in Tables 3 and 4 are examined, it can be seen that though the accuracy of many of the individual readings are questionable, the averages are meaningful. This is statistically defensible, since individual doses will be overreported as well as underreported or missed. It is advisable to make note for the legal record files of the conditions or limits of accuracy. but record "detected" doses. The most important factors to

TABLE 3. REACTOR CONTAINMENT ENTRY DOSES 10/16/80

		Badges Worn Outside of Clothing					
		Harshaw		INEL		Panasonic	
Personnel	ORD[a]	nonpen (mrad)	pen (mR)	nonpen (mrad)	pen (mR)	nonpen (mrad)	pen (mR)
1	515	0.0	490	164	308	0.0	490
2	410	0.0	510	153	332	0.0	460
3	262	0.0	320	59	218	0.0	300
4	367	0.0	390	73	255	0.0	400
5	198	15	210	181	139	0.0	200
Average	350	3	384	126	250	0.0	370
% Difference	40%	98%	54%				50%

a. Direct Reading Dosimeter readings are expected to read high since (1) the case is only approximately 300 mg/cm^2 thick, and (2) electrical leakage would cause an upscale reading.

keep in mind are that (1) individual nonpen doses of several hundred mrad could be "missed" or overreported under the least favorable conditions, but (2) long-term individual dose averages would be more accurate.

Angular Response - Figure 3 illustrates the effect in beta dosimetry when the badge itself shields the dosimeters from the nonpen radiation because the source is at an angle different from "straight ahead" or 0^{o}. The INEL Badge design places the dosimeters above the badge in a small hemisphere of plastic. This design minimizes the angular response or "shadowing" by the badge, compared to "flat" badges with the dosimeter recessed such that the thickness of plastic and other materials comprising the badge structure itself offer greater shielding from the side than from

TABLE 4. REACTOR CONTAINMENT ENTRY DOSES 11/13/80

Personnel	DRD[a]	Harshaw 2-chip nonpen (mrad)	Harshaw 2-chip pen (mR)	INEL nonpen (mrad)	INEL pen (mR)	Panasonic nonpen (mrad)	Panasonic pen (mR)
		Badges Worn Outside Clothing					
1		0.0	390	186	328	-	-
2		0.0	190	815	176	0	180
3		360	390	1035	302	160	290
4		0.0	330	53	308	0	290
5		0.0	220	35	209	0	200
6		160	290	348	223	0	260
7		0.0	360	4371[b]	291	0	330
8		55	270	309	233	130	220
9		200	360	367	271	0	260
10		60	320	242	287	120	270
11		0.0	210	44	199	0	180
Average		76	303	343	257	41	248
% Difference from INEL		-78%	-18%			-88%	-4%
		Badges Worn Inside Clothing					
1	375	0.0	330	37	295	0	250
2	195	0.0	180	0.0	173	0	170
3	370	0.0	330	560	327	0	280
4	375	0.0	320	18	302	0	270
5	225	0.0	220	78	199	0	170
6	300	0.0	260	0.0	275	0	250
7	363	0.0	320	177	307	0	290
8	295	0.0	240	300	219	0	210
9	335	0.0	320	307	268	0	260
10	338	0.0	300	124	269	0	260
11	208	0.0	200	68	186	0	200
Average	307	0.0	275	152	256	0	237
% Difference from INEL	20%	-100%	7%			-100%	-7%

a. Direct Reading Dosimeter readings are expected to read high since (1) the case is only approximately 300 mg/cm^2 thick, and (2) electrical leakage would cause an upscale reading.

b. This result appears to be an oulier and was not used in the averaging.

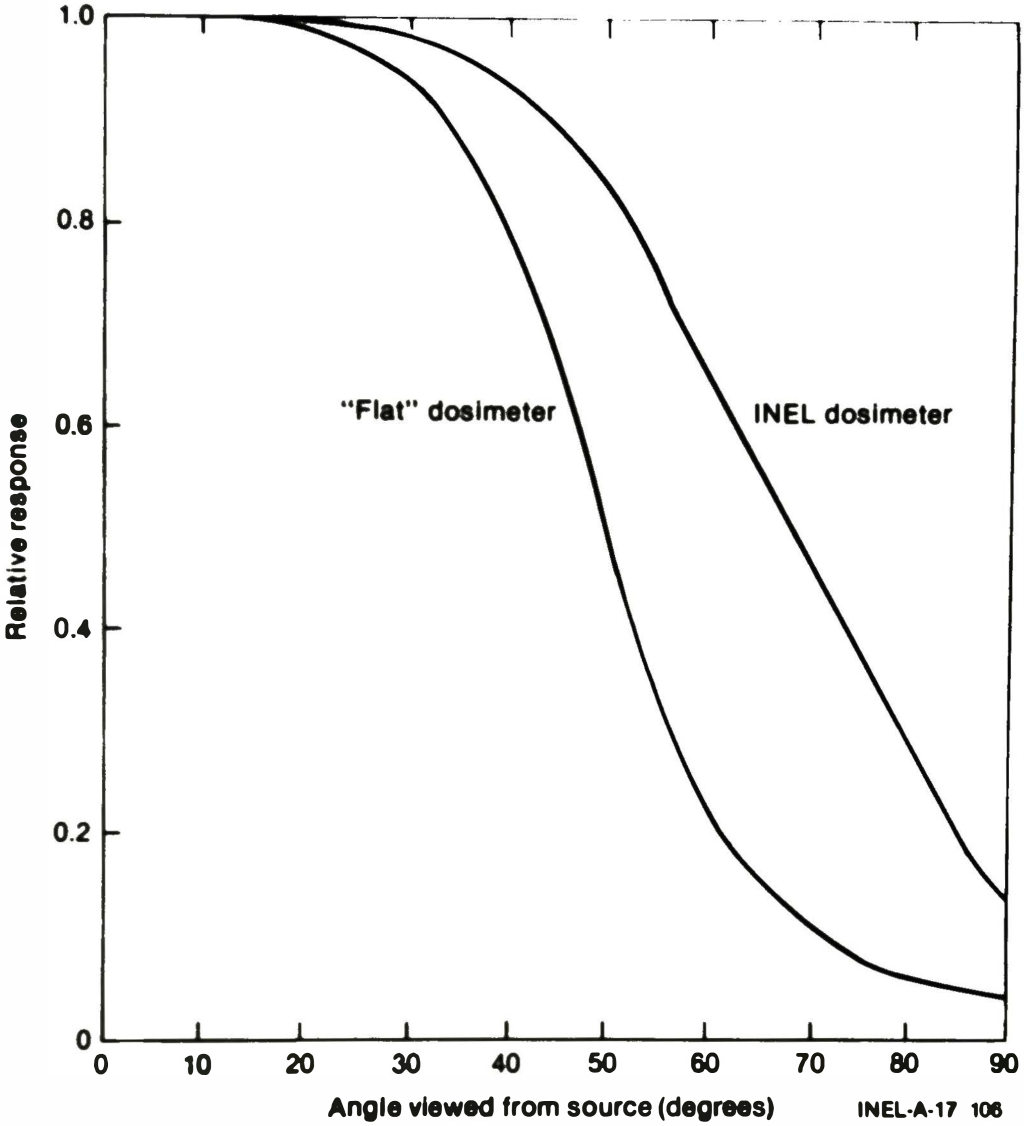

Figure 3. Angular response of dosimeters.

the front. Further confusion can result from "missing" the pen filter from the side. The data in Figure 3 indicate that at 60^{o} the response of the INEL badge is only 30% lower than at 0^{o}, compared with 80% reduction on a flat badge for Sr-90 source energies. Preliminary data taken at TMI with Tl-204 energies verify this effect. Both the Harshaw and Panasonic badges are flat badges with recessed TLD detectors. Much more data are necessary to establish comparable response curves for the dosimetes under consideration.

Fading and Residual Readings - Long experience at the INEL and elsewhere[9] has established the desireability of a 16-hour 80^{o}C, preexposure anneal. The need for a preread anneal was evaluated as indicated in Table 5:

TABLE 5. DOSIMETRY COMPARISON

Group	Number of Chips	Protocol[a]	Response (mR)	Std Dev. (%)
A	20	24 hr postexposure wait	314.0	1.2
B	20	1 hr postexposure wait	313.6	1.1
C	20	20 min 100^{o}C preread anneal	313.7	2.7
0	20	10 min 100^{o}C preread anneal	312.8	1.6
E	20	No exposure 10 min 100^{o}C preread anneal (control)	8.7	1.7

a. All badges received a 16-hr preexposure anneal and a nominal 300 mR exposure.

The conclusion was that with a 16-hr 80^{o}C preexposure anneal the badges could be read out with excellent accuracy following as little as a 1 hr postexposure wait and no preread annealing.

Metal Filter Effects - The use of heavy metal (Pb) filters in badges to provide the required penetrating shield thickness and to "flatten" energy response of energy dependent detectors is technically inadvisable, due to the fact that high energy beta particles produce bremsstrahlung radiation (x-rays) when slowed or stopped near atoms with large atomic numbers. This is avoided in the INEL badge by the use of plastic filters only. However, it is estimated that errors introduced as a result of a metal filter would be in the order of a few percent and should not be a major consideration in the selection of the badge.

Dosimeter Comparison

As the INEL dosimeter beta and gamma response was established and verified, it became important to establish comparative response characteristics in other dosimeters that could be considered as viable options on the basis of convenience or for other operational reasons. A brief comparison was made with the available dosimeters listed above. Each of the dosimeters was given the same dose from the TMI sources, and the "observed" dose compared. Time and nonavailability prevented investigation of the practicability of modifying the Panasonic and Harshaw badges to provide improved or maximized response. Values are those reported directly from the systems as they exist. While we have every confidence that with judicial modifications of badge design and careful calibration and development of response evaluation techniques, both systems could be made to respond in a roughly equivalent manner, this remains to be done.

The results of the calibrated source exposure comparison are listed in Table 6. An examination of the data leads to several specific conclusions:

- o The INEL dosimeter responds as expected, with a small (10%) nonpen component indicated at a 0.662 Mev gamma only exposure. This is a predicted response, which should be, but has not yet been, corrected in the algorithms. This correction will be made before implementation of a routine field system.

- o The INEL badge responds predictably, with ability to accurately resolve pen and nonpen doses, showing approximately 30% over-response to Tl energy betas (0.77 Mev maximum).

- The Panasonic badge[a] shows variable pen response from 10 to 60% high, and an equally variable nonpen response from 10% high to a factor of approximately 2 low. This badge also showed a nonpen dose 115% higher than the pen dose when no nonpen dose was received. The reasons for the anomalies in this badge are not completely understood at this time.

- The Harshaw 2-chip badge[b] reported values both high and low for reasons previously discussed. This comparison provides further indication of inadequate design.

- The Film dosimeter responded more poorly than expected. Though previous tests indicated a more reliable response, this test was more rigorous through exposure of the test badges to 2 different isotopic sources (Sr/Y-90 and Tl-204). Time was not available to repeat the exposures or verify the reported response. Pen dose was variable from 40% low to 20% high with the nonpen dose from 10% to a factor of 2 low. In addition, one set of reported Sr/Y-90 results were so completely different from the delivered dose that systematic error was obvious, and the data were not recorded or used.

- The Harshaw 4-chip badge was not completed in time for the intercalibration.

The technical response of the INEL dosimeter is clearly superior in this test. This is to be expected since (a) the INEL badge design was specifically created for the mixed-field problems encountered at TMI represented in the test, (b) considerable effort over a three-month period on the INEL system had ironed out most of the anomalies in the prototype

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a. It is expected that this dosimeter design can be improved.

b. Although inaccuracies of the 2-chip system were previously demonstrated and accepted, this dosimeter was included for comparison purposes.

TABLE 6. DOSIMETER COMPARISON

DELIVERED TISSUE DOSE (mrad)[a]			MEASURED TISSUE DOSE (MRAD) (RATIO OF MEASURED TO DELIVERED DOSE, MRAD)							
	E_r 0.546 + 2.27[b] E_t 1.71 E_a 0.646	E_r 0.766[b] E_t 0.622 E_a 0.299	INEL		Panasonic		Landauer Film		Harshaw 2 chip[e]	
0.662 Cs-137	Sr/Y-90	Tl-204	Pen[c]	Nonpen[d]	Pen	Nonpen	Pen	Nonpen	Pen	Nonpen
174	0	0	178 (1.0)	16.4 -	248 (1.4)	200 -	195 (1.1)	0.0 (1.0)	170 (0.98)	0 (1.0)
0	617	0	0 (1.0)	580 (0.9)	13.2 -	542 (0.9)	0 (1.0)	293 (0.5)	134 -	922 (1.5)
45.6	625	0	47.4 (1.0)	630 (1.0)	68.4 (1.5)	572 (0.9)	40 (0.9)	0.0[f]	168 (3.7)	866 (1.4)
81	1151	0	99 (1.2)	1237 (1.1)	141 (1.7)	1170 (1.0)	108 (1.3)	550 (0.5)	354 (4.4)	1880 (1.6)
40.9	309	277	46 (1.1)	578 (1.0)	65 (1.6)	471 (0.8)	40 (1.0)	233 (0.4)	120 (2.9)	560 (1.0)
40.4	0	574	48 (1.2)	695 (1.2)	57 (1.4)	408 (0.7)	50 (1.2)	448 (0.8)	51 (1.3)	238 (0.4)
0	0	574	0 (1.0)	655 (1.1)	1.1 -	320 (0.5)	0 (1.0)	363 (0.6)	0 (1.0)	260 (0.5)

a. mrad = dose in tissue at depth indicated. Delivered Dose was calculated using extrapolation chamber measurements in the same configuration used in badge irradiations and converted to tissue dose. As reported in Appendix A, these values are 20-30% higher than NBS measurements. Differences in calibration configurations and tissue, versus water dose conversion, account for part of the discrepancy. Though there are unresolved discrepancies, the conclusions are not altered.

b. Calibration of the Sources in the configuration used during badge irradiation indicated considerable differences in theoretical and actual energies. E_r = Theoretical E_{max} MeV; E_a = actual or measured average energy in MeV; E_t = Measured E_{max}.

c. Pen = Penetrating at 1 cm depth in tissue.

d. Nonpen = Nonpenetrating or at a depth of 0.007 cm in tissue.

system, and (c) no effort was made to modify the design, calibration, or calculational procedures for the other dosimeters being compared. The value of the comparison is in the demonstration that basic changes and development would be necessary (even if possible) to bring any of the systems compared to an equivalent level of technical accuracy. The experience in developing the INEL prototype system would shorten the time necessary to place another system in operational status at its inherent design limits.

Data in Tables 3 and 4 were collected by placing three different dosimeters on each individual during actual entries into the contaminated TMI-2 containment building. These results indicate that the Panasonic and Harshaw 2-chip dosimeters consistently record a lower nonpenetrating dose and the Harshaw 2-chip records a higher penetrating dose. The differences were greater on the 10/16/80 entry. The 11/13/80 entry data are instructive when the following facts are noted:

- The average readings based on the actual containment entry data on the INEL badge indicate no change in the penetrating component from inside to outside of the protective clothing. The Panasonic and Harshaw badges show a 3% and 11% drop, respectively in average penetrating component through the clothing, which is not technically predicted since gamma radiation would not be expected to be attenuated by clothing. Clothing would attenuate beta radiation, however, so these data suggest that beta radiation is interferring with the measurement of penetrating radiation.

- The Harshaw badge produced higher penetrating doses in the range of 7 to 18%. The Panasonic gave 4 to 7% lower values. The higher penetrating results were expected in the Harshaw badge, due to beta penetration to the pen chip.

It is recognized that the comparisons are not extensive, and the statistics could be improved by further study. However, it appears clear that the environmental Panasonic (dosimeter tested) and the Harshaw 2-chip badges (as presently constructed) do not record the penetrating component of the absorbed dose with a comparable degree of accuracy, and underestimate the nonpenetrating component. Consistency also appears to be a problem in both of these dosimeter systems.

Recent Findings at the INEL

The INEL dosimeters have continued to undergo testing at the INEL, concurrent with the preparation of this report, for increased application at the INEL and in response to the draft ANSI N13.11 standard soon to be released. Very recent data, obtained during what was to have been the final review of this report, indicates that the current prototype of the INEL badge exhibits an overresponse to x-rays in the region of 100 keV to 15 keV (the lowest energy tested). The observed overresponse was relative to the deep dose equivalent values specified in the ANSI standard N13.11 draft, "Criteria for Testing Personnel Dosimetry Performance." The overresponse, which amounts to about a factor of three at 15 keV and diminishes to about 9% at 100 keV, is higher than expected on the basis of the small intrinsic overresponse of LiF.

Subsequent analyses suggested that the badge material (ABS plastic) is not sufficiently tissue equivalent at low photon energies. At those low energies the photoelectric effect, which is very sensitive to atomic number, is the predominate absorption mechanism. As a result, the badge becomes less absorbing than tissue at those low energies, leading to the observed overresponse.

While these x-ray tests were being carried out, the "old," flat INEL 2-chip (LiF) dosimeter current in use was also tested. This dosimeter has a 540 mg/cm^2 aluminum filter on the front and back of the penetrating chip. The front has approximately an additional 100 mg/cm^2 of plastic. The x-ray response of this dosimeter was found to be essentially perfect relative to delivered deep dose values calculated from the ANSI N13.11 draft standard. This excellent x-ray response is fortuitous, since the "old" INEL dosimeter was not even designed for x-rays. Apparently, the thickness of less than 1000 mg/cm^2 of aluminum and plastic, taken together with the higher atomic number of aluminum (relative to tissue), combine to offset the intrinsic overresponse of LiF, and produce a nearly perfect photon response down to 15 keV.

Other recent data obtained at the INEL suggest that the new INEL dosimeter responds well to moderated fission neutron spectra but overresponds to pure thermal neutrons.

Other Considerations

As summarized in Table 7 there are other aspects which would affect a choice of a dosimeter system and are discussed as follows:

- Neutron response is necessary for an operating reactor, though not needed at TMI-2 at present. It would appear desirable to install a system that could be used at both Units 1 and 2. The INEL badge is boron loaded and can be used as a neutron albedo dosimeter. Neutron dosimetry with the other systems requires a separate badge. Recent data obtained at the INEL indicate an overexposure to a pure thermal neutron spectrum but good response to moderated fission spectra (typical of routine fields at an operating reactor).

- Space for emergency response foils and dosimeters have been designed in the INEL dosimeter. The other badges are less well designed in this respect, though the Harshaw 4-chip badge has space for a few small foils.

- Availability is roughly equivalent for the new systems that must be installed and calibrated. A second Harshaw hot gas reader has been received and modified to provide semiautomatic processing. These readers are immediately available in "semiautomatic" form with a fully automated prototype expected within 12 months. The other TLD systems, though commercially available on a 90 day basis, would require extensive evaluation, modification, and calibration.

TABLE 7. FURTHER ELEMENTS OF DOSIMETRY COMPARISON CONSIDERATION

Dosimeter	β Response	N Monitoring	Emerg. Dos.	Availability	Reader and Equip.	4K Dosimeters	Automation	Fragility
INEL	State-of-the-art	Albedo Design-same badge	Yes	Manual: 3 mos. Semiauto: 6 mos.	$25,000 to $30,000 - No cost to GPU during recovery	44,000[a]	Semiauto Only at present - More handling of TLDs and badge	TLD-rugged
					44,000 Total			
Harshaw 2 Chip	Very poor	None - 2nd badge needed	No - 2nd badge needed	In service	In service	In service	Semiauto-relatively convenient	TLD-rugged
Panasonic	Currently variable and/or unpredictable	Panasonic N badge available - 2nd badge needed	No - 2nd badge needed	4-6 mos.	$150,000	$100,000[b]	Yes - very convenient	TLD-rugged
					250,000 Total			
Landaur		High energy	No	Immediate	NA Approximately $5/badge/month or 100,000 to 200,000 per year	NA	NA	Very Poor
Harshaw 4 Chip	Unknown, could be good	Not designed	Yes	4-6 mos.	$30,000 to $50,000	$32,000[c]	Semiauto only but relatively convenient due to TLD card system	TLD-rugged
					60,000 to 80,000 Total			

a. Cost is approximately $8 for 4 TLDs per badge, plus approximately $2 per badge, plus $1 for criticality (emergency) foils.

b. Cost is $25 per badge.

c. Cost is regularly $17 per 4-chip badge. Harshaw quoted 2-chip badge exchange for a difference of $5 per badge, plus approximately $3 for new 4-chip badge.

- A cursory comparison of costs indicates that the INEL system is the least expensive, by a considerable margin. This major difference results from the fact that the INEL semiautomated reader and equipment have been purchased and modified by DOE and would be available for the duration of the recovery operations on a loan basis.

- The major disadvantage of film is the extreme fragility and sensitivity of the dosimeter to heat, humidity, pressure, fading, mechanical damage, etc.

- Most personnel dosimeters, including the INEL badge, require careful orientation during use.

Implications of Recent INEL Data

The excellent photon response of the "old," flat INEL dosimeter suggests an inexpensive solution to the near-term TMI dosimetry problem. An excellent photon-responding dosimeter should be obtainable by simply fabricating thicker aluminum filters for the Harshaw 2-chip system presently in use at TMI. The thicker filtration would be chosen to match that of the "old," flat INEL dosimeter. The additional filtration should ensure excellent photon response down to 15 keV and exclude almost all of the beta radiation from the penetrating detector, thus eliminating one of the major drawbacks of the present 2-chip Harshaw system. The modified 2-chip Harshaw system would, of course, have to be tested in photon, beta, and mixed fields. The beta response of the Harshaw 2-chip system could be improved slightly by making the thin window thinner, but the dosimeter would still have a strong beta energy dependence.

The beta response of the INEL badge has been studied at both TMI and the INEL, and it appears to be superior to anything else tested. The INEL dosimeter could be used to supplement the proposed modified Harshaw 2-chip system for the relatively few personnel involved in those applications such as containment reentry where high-quality beta dosimetry is required.

Both the Harshaw 2-chip and the INEL dosimetry systems are in place and could be operating at TMI as soon as INEL badges in sufficient supply are obtained. The Harshaw 2-chip system should be easy and inexpensive to modify and test, and could be used on all radiation workers. The smaller number of personnel involved with reentry. or other situations where high beta/gamma ratio fields could be encountered, could be additionally badged with the manually operated INEL badge (with badge handling improvements) to record the beta doses.

Alternatives for Dosimetry at TMI

Alternative 1: Combination of the Harsaw 2-chip and INEL Dosimeters

A modified Harshaw 2-chip system with a thicker penetrating filter combined with the INEL dosimeter would serve the interim during which a permanent system is designed, purchased, and installed. This combination appears to be technically sound and relatively simple, and capable of rapid, low cost implementation that will provide significant and immediate upgrade. Technical and administrative procedures now used for the Harshaw 2-chip system could be retained. The INEL system could be used to supplement the Harshaw 2-chip system where high-quality beta dosimetry is required and could be operated semiautomatically, that is, capper-uncapper and chip reading would be automatic with all other operations manual.

Alternative 2: Acquistion, Testing, and Implementation of a Fully Automatic System

A fully automatic system, such as the Panasonic or Harsaw 4-chip system is expected to be technically sound but would take longer to test and implement than Alternative 1. It would require a high initial capital outlay. And though ultimately the acquisition of a fully automatic system is desirable, more would probably be gained by waiting. Personnel dosimetry is currently under great technical advancement. The ANSI N13.11 standard is close to approval but not yet approved, and NRC implementation guides and programs will follow. The two fully automatic systems available are both relatively new. It would thus seem prudent to accrue more experience with these systems, especially in terms of performance relative to ANSI N13.11, before making a decision.

Alternative 3: Use of Dosimetry Services

Services exist that could possibly meet technical requirements. They would have to be tested against the special mixed-field conditions found in the TMI containment, however. The service would require little if any initial capital outlay but probably a badge could not be developed in time for employees engaged in reentry and recovery.

CONCLUSIONS AND RECOMMENDATIONS

Experience at the INEL, calibrating and testing of the prototype system at TMI, and cursory technical evaluation of other available systems in service lead to the following conclusions:

- o The INEL Dosimeter System response appears significantly more accurate for beta dosimetry when compared with other available dosimeter systems. Of the systems known or tested, the INEL system appears to be the best-designed badge. The development of the INEL system is advanced but not yet complete, and recent INEL data indicate possible problems with x-ray and thermal neutron response.

- o The Harshaw 2-chip badge with 270 mg/cm^2 penetrating filter has been shown to have specific limitations, overestimating the penetrating dose and unreliably estimating the nonpenetrating dose. It could be significantly improved, however, by increasing the penetrating filter to 540 mg/cm^2 of aluminum and 90 mg/cm^2 of plastic, and by reducing the thickness of the nonpenetrating filter.

- o The multiple filter TLD systems compared could probably be modified and calibrated to produce results equivalent to the INEL system, though not without significant development time and costs.

- o Costs to GPU of modifying the present 2-chip Harshaw dosimeter should be low.

- o Costs to GPU associated with fielding the INEL system for a limited number of workers appear significantly lower than for other available multiple filter systems, and particularly low for the recommended usage.

- Angular response of the INEL system appears superior to the other dosimeters.

- The INEL system will not be immediately available as a fully-automatic system, hence some increased handling of the badges will be necessary.

- The beta response of the film service on this test was not satisfactory. This, together with the inherent fragility of film, would not argue for its choice as the reentry dosimeter.

- A completely operational INEL system for beta dosimetry can probably be obtained and placed in service within three months.

- Further research into beta dosimetry principles is necessary to reduce the current limitations of beta dosimeters.

- Use of the INEL and modified 2-chip system, or other equally accurate systems, will prevent overreporting of penetrating dose, allow more productive time in the field, and yield overall ALARA improvement.

Based on the conclusions summarized above, the following recommendations are made:

- The standard Harshaw 2-chip badge should be removed from re-entry service at the earliest possible time. Specific documentation should be formulated to record the fact that previously reported penetrating doses to personnel at 1 cm tissue depth is higher than the actual dose.

- The Harshaw 2-chip badge should be modified by increasing the penetrating filter to 650 mg/cm^2 and reducing the nonpenetrating window as much as practicable. It should then be calibrated for photons and betas and used to replace the standard Harshaw 2-chip badge.

- Adequate photon dosimetry can be performed on all routinely monitored personnel with a modified Harshaw 2-chip dosimeter, and reentry/recovery personnel can be additionally badged with the INEL dosimeter to provide state-of-the-art beta dosimetry. The present INEL prototype system should be used on an interim basis to record nonpenetrating re-entry/recovery personnel dose, while semiautomatic equipment is being received, evaluated, installed, and calibrated.

- Badges, TLDs, an automatic decapper and other equipment and training should be obtained as soon as possible for instituting the interim INEL field system.

- Calibration of the new dosimeter system and training in its use and field survey techniques should be completed at TMI as soon as possible.

- If operational convenience resulting from a fully automated system or other similar criteria dictate the choice of another system, that system should be carefully evaluated and modified as needed prior to purchase and then carefully installed and calibrated.

- Development of personnel dosimetry is currently moving rapidly and will undoubtedly be additionally affected when the draft ANSI N13.11 standard is approved and related NRC guides are issued. The available fully automatic systems are rleative new, and it is therefore prudent to defer a decision on acquisition of an expensive, fully automated system until after approval of ANSI

N13.11 and after more experience with the available, fully automatic systems has accrued. However, the critical assurance, which is the key to a successful dosimeter program, is the adequate design of the dosimeter and badge.

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APPENDIX A

SOURCE CHARACTERIZATION

APPENDIX A

SOURCE CHARACTERIZATION

The construction of beta calibration sources within the nuclear industry has been very limited, consisting primarily of Sr/Y-90 sources. The techniques of construction, as well as the source isotope choice, can have a marked effect on the spectra and dose rate from the source; e.g., sources mounted by electroplating would be different when compared to sources incorporated into a resin matrix. Even variations vs. distance from the source must be carefully evaluated because of significant air absorption.

What few sources have been available have been inadequately calibrated or understood. For example, it is common to quote the response of a detector to the theoretical end point or maximum energy of the beta continuum. Even a casual familiarity with the problem would make it clear that few if any of the betas interacting with the detector would be of this energy, most of the response coming from betas considerably lower in energy.

This study used a specially developed NE 102 plastic scintillation spectrometer and an extrapolation chamber. These instruments were used to define the source spectra and dose rate at various distances and absorber thicknesses. They were used to characterize the beta sources used in the personnel dosimetry calibrations for dose rate and spectral qualities under the same test configurations and conditions that were used during the badge irradiations. In addition, a series of characterization measurements were made as a function of absorber thickness, since a knowledge of absorber effects allows the interpretation of dosimeter response resulting from absorption internal to the dosimeter and an understanding of spectral changes from absorption external to the dosimeter.

The beta sources utilized in this project were fabricated by Amersham and are briefly described as follows:

- Pm-147 as a carbonate, incorporated in a rolled silver foil face, 3-micron thick, with a 2-micron paladium coating, for a total covering of 5.6 mg/cm^2.

- Tl-204 as thallous chromate incorporated in a rolled silver foil face 20 micron thick or 20 mg/cm^2.

- Sr/Y-90 point source, incorporated in a 1-mm diameter glass bead and sealed in a welded stainless steel capsule. The window thickness is 50 microns or 40 mg/cm^2.

The results of the spectral measurements documented in Tables A-1 and A-2 and Figures A-1 through A-6 can be explained and predicted from physical theory but will undoubtedly be informative and should be a significant aid in interpreting, predicting, and controlling field dose response. The dose rate curves were consistent with those reported by NBS, though somewhat higher in level. The dose rate curves under the configuration tested did not show a simple exponential attenuation, which indicates the need to reevaluate the standard calculational algorithms in use with the INEL dosimeter.

A Victoreen extrapolation chamber was used for the dose rate measurements with a Victoreen-500 electrometer. Dose rates were calcualted using the formula

$$R \frac{rad}{s} = \frac{W \times s}{A \times Pa} \frac{760}{273} \frac{273 + T}{P} E \frac{dI}{dx}$$

where

E	=	10^{-6}
W	=	33.73 average energy for ion pair production in air
s	=	1.13 for conversion of air dose to tissue dose
A	=	13.2 cm^2, area of the collecting electrode
T	=	temp in ^oC
P	=	pressure in mm Hg

I = the chamber current in pA

x = the electrode separation in mm

Pa = density of air at STP.

As previously indicated, dose was determined at the distances and configurations used for dosimeter testing and calibration. Additional dose rates were determined using absorbers of mylar, each absorber having a thickness of 14 mg/cm^2. The results are shown in Table A-1 and are 20 to 30% higher than those reported by NBS.

Spectra were taken using a plastic scintillator (NE102) 1 cm thick with a 1.9 cm diameter, at various distances and with various absorber thicknesses. Again, the distances used corresponded to those used for dosimeter calibration and testing. The results demonstrate that significant changes in the end point and average energies of the spectra occur with absorber thickness. The present spectra of the sources (Table A-1 and Figures A-1 to A-3) show the effects of absorption by the packaging materials of the sources and air.

A surprising finding of the characterization work with the Pm-147 source was the unusually high levels of Pm-146 contamination. The manufacturer's reported contamination level is 2.61 Ci Pm-146 per Ci of Pm-147 or 2.6 x 10^{-4}% (corrected for decay). The spectra in Figure A-3 show Pm-146 at approximately 1% of the Pm-147 by activity and approximately 5% by energy. The apparent discrepancy in the manufacturer's analysis of the source matrix and the observed radiation from the source may be explained by differential absorption of the different energies by a large amount of absorber resulting from the construction materials and technique of mounting. However, calculations based on the absorber reported by the manufacturer and the absorber calculated from end-point energy loss (21-22 mg/cm^2 for detector, air and packaging) indicate that only 7% of the Pm-147 beta particle have sufficient energy to reach the detector. This amount of absorber is insufficient to account for the observed activity, which leads to the conclusion that either Pm-146 contamination is greater than reported or that all the absorption or other mechanisms of loss have not been accounted for.

TABLE A-1. DOSE RATE AND SPECTRA INFORMATION WITH ABSORBER

Absorber mg/cm^2	E_o KeV	E KeV	$\dot{D}$ rad/s INEL	NBS
Sr/Y-90 at 22.3 cm 2nCi point source				
0	1709	646	8.2×10^{-4}	6.4×10^{-4}
14			7.8×10^{-4}	
28	1700	628	7.4×10^{-4}	
70	1644	612	6.9×10^{-4}	
140	1644	638	5.6×10^{-4}	
280	1467	577	3.6×10^{-4}	
420	1300	438		
700	910	310		
980	418	165		
Tl 204 at 20 cm 1/2 source				
0	622	249	4.4×10^{-2}	3.6×10^{-2}
14	585	254		
42	538	259		
84	483	197		
126	399	166		
182	306	115		
Tl 204 at 10 cm 1/2 source				
0	725	275	4.4×10^{-2}	3.6×10^{-2}
14	678	238	3.8×10^{-2}	
28	632	242	3.4×10^{-2}	
70	530	220	2.7×10^{-2}	
84	-	-	1.2×10^{-2}	
98	453	172		
140	390	155		
182	305	125		
Pm 147 10 cm				
0	-	-	8.6×10^{-3}	
14	-	-	7.7×10^{-4}	
28	-	-	3.11×10^{-5}	

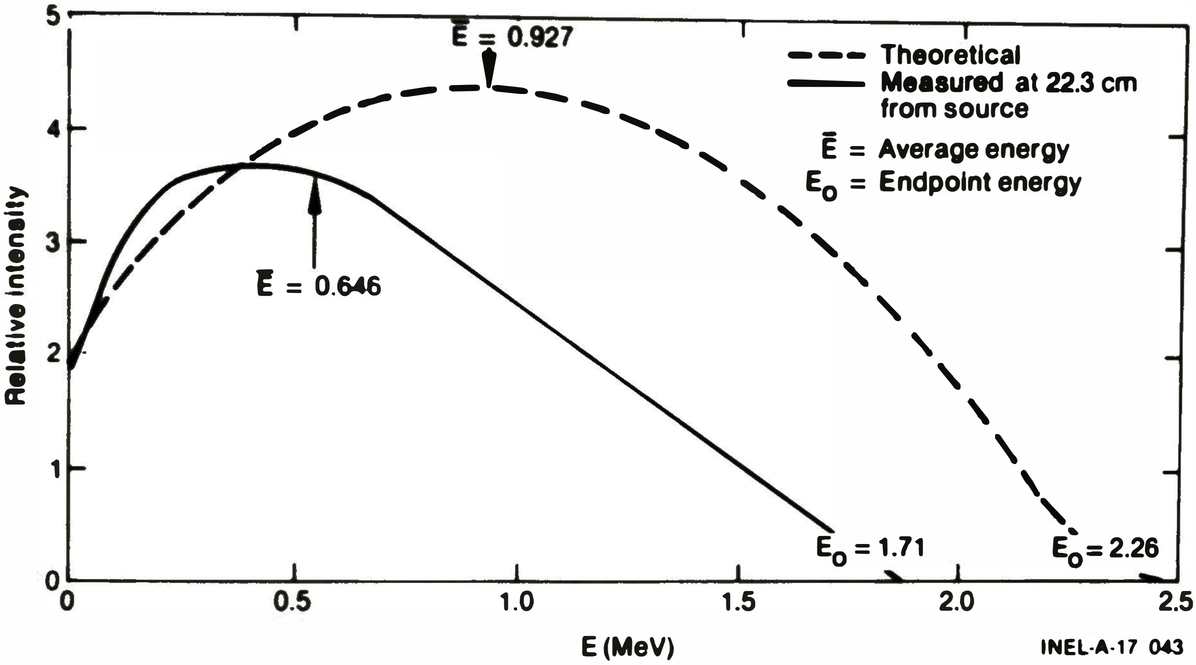

Figure A-1 Comparison of measured-to-theoretical B spectra for Sr/Y-90.

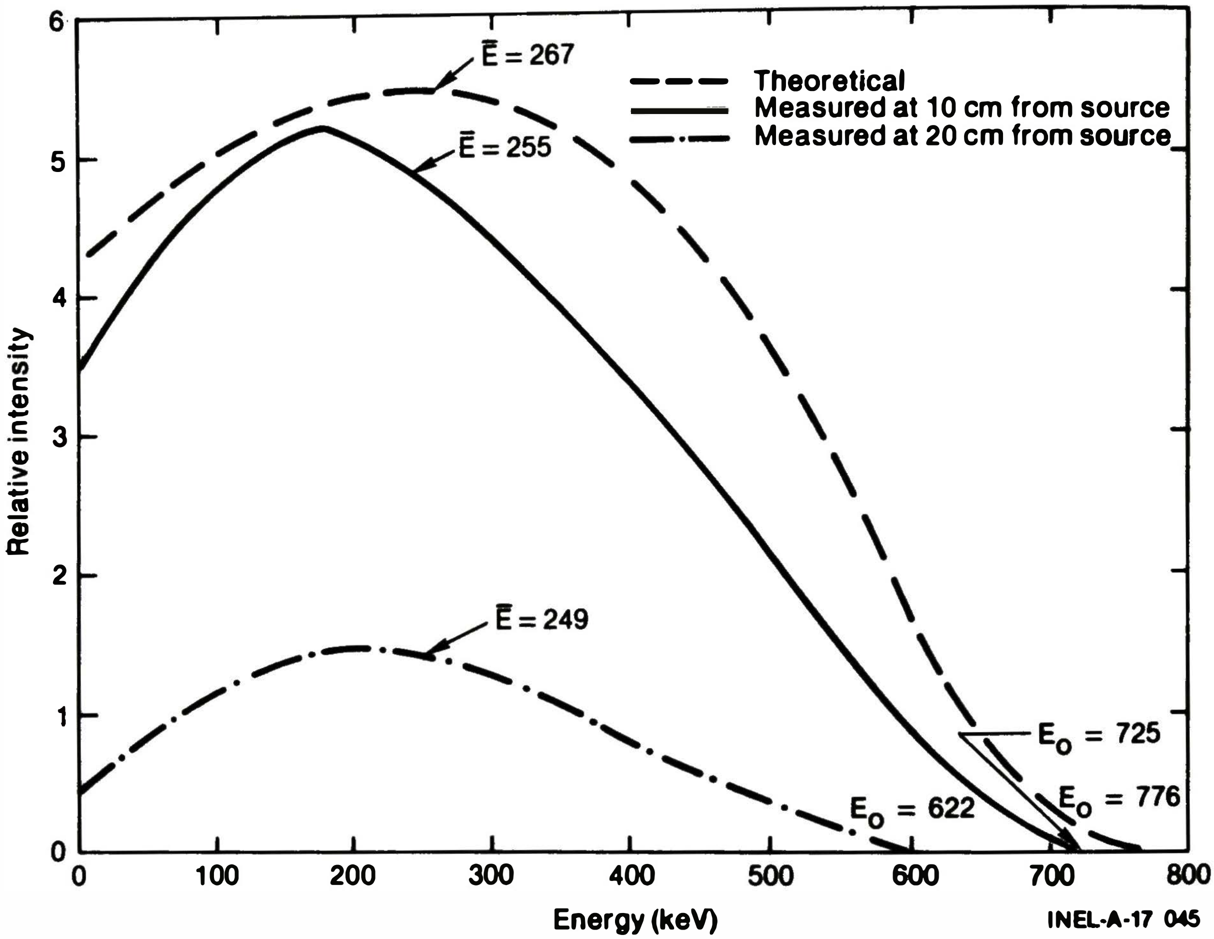

Figure A-2 Comparison of measured-to-theoretical B spectra for Tl-204.

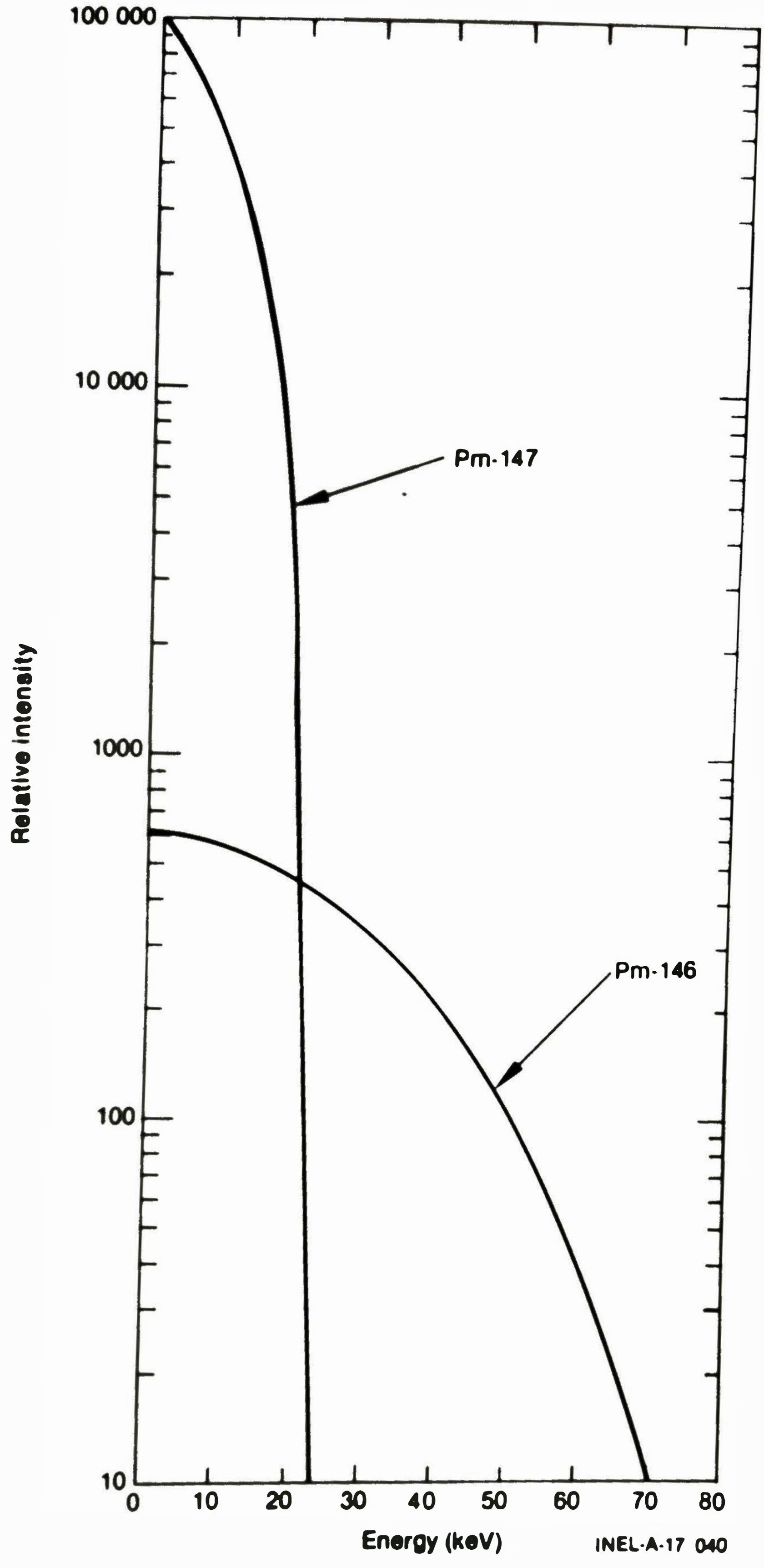

Figure A-3 Measured B spectra for the promethium source.

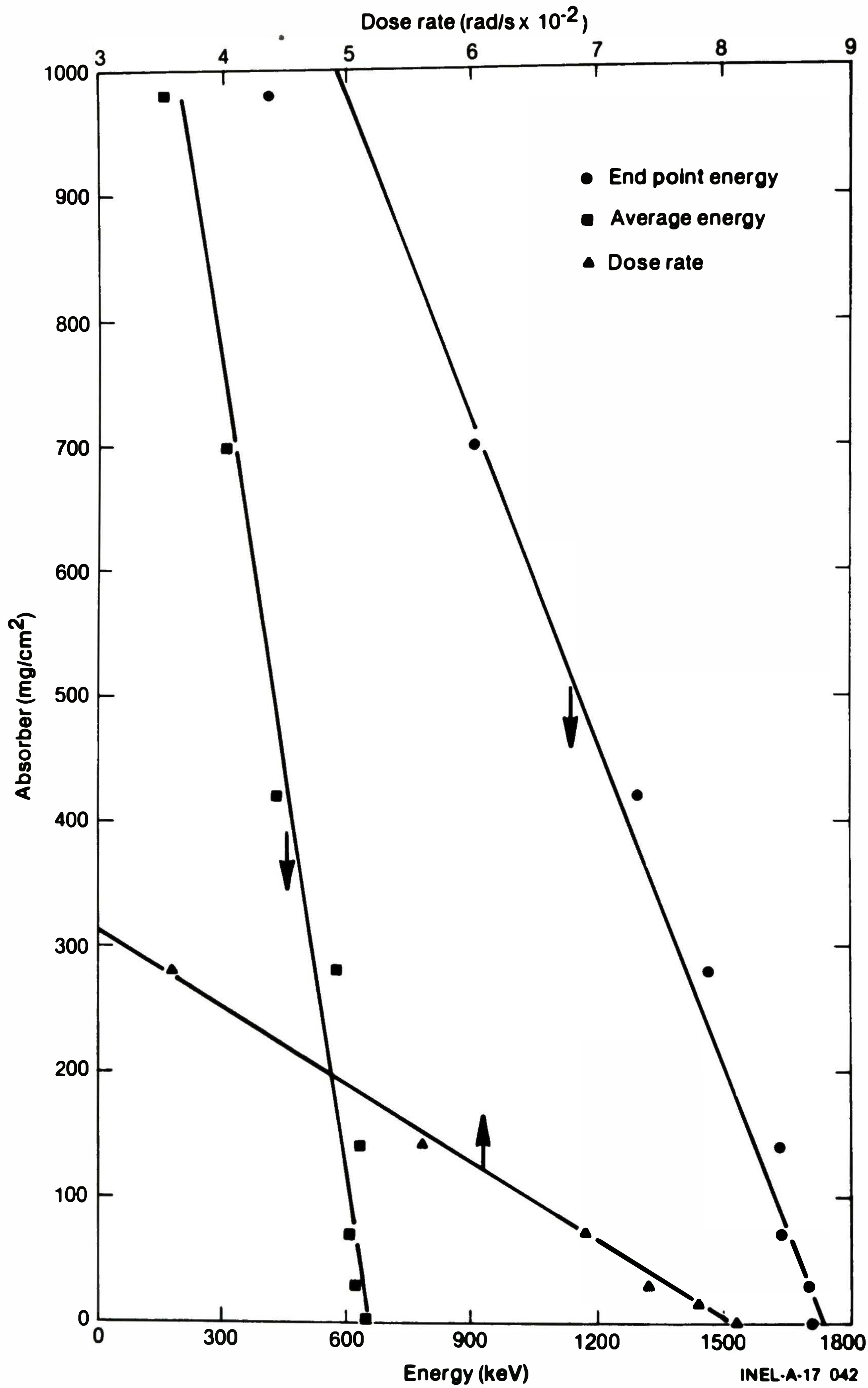

Figure A-4 Dose rate and energy response vs. absorber Sr/Y-90.

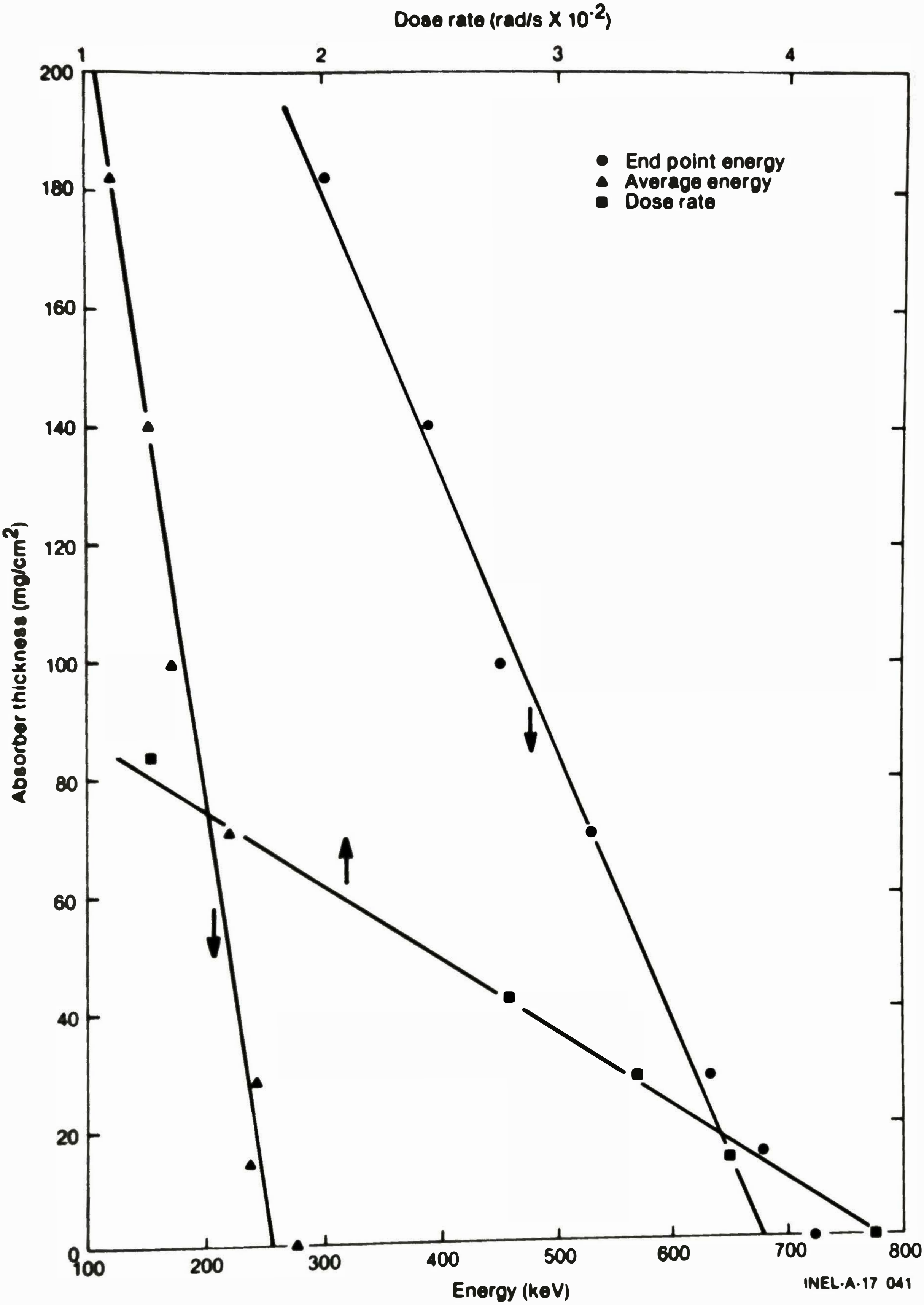

Figure A-5 Dose rate and energy response vs. absorber TL-204 (10 cm).

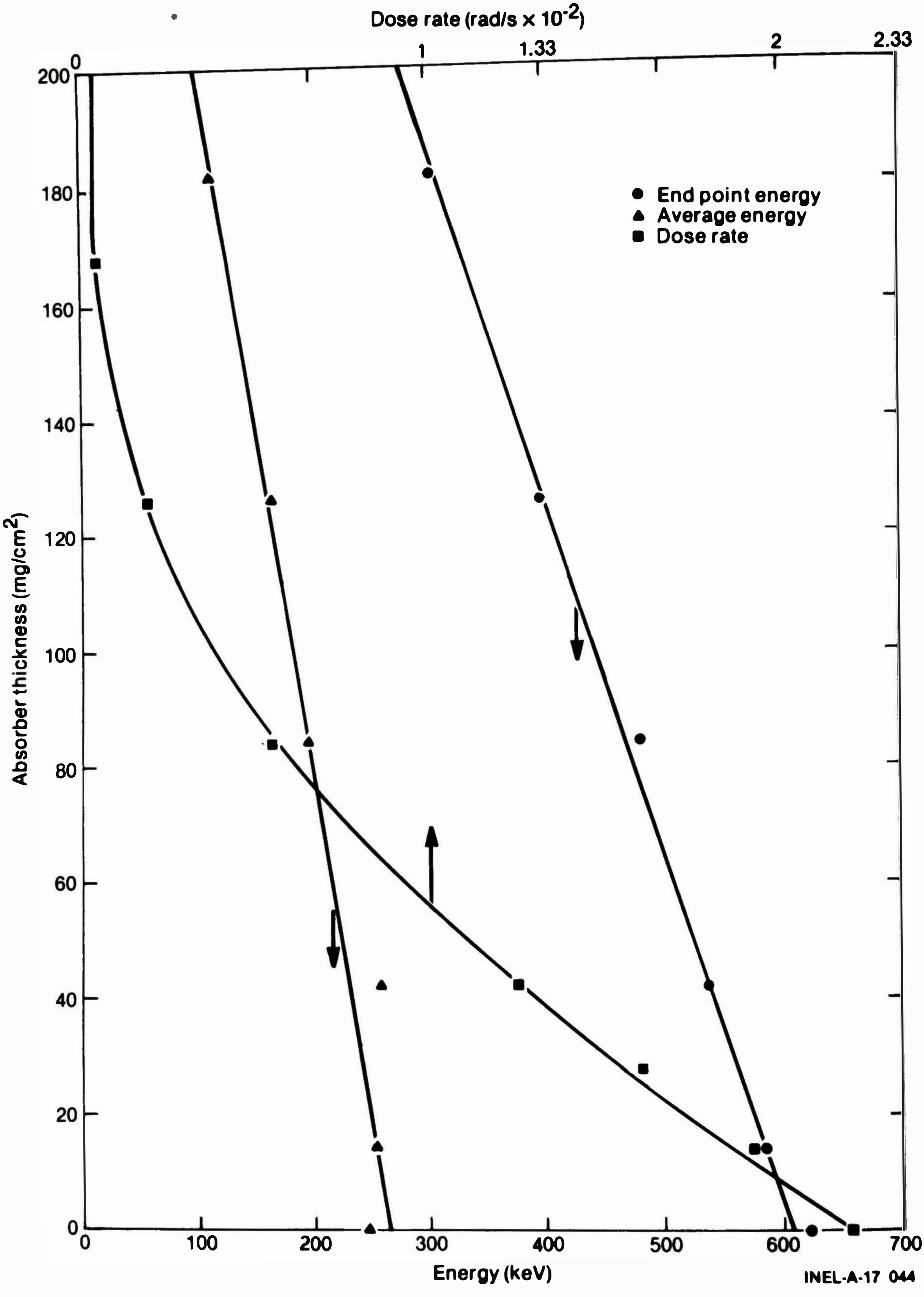

Figure A-6 Dose rate and energy response vs. absorber Tl-204 (20 cm).

Absorber effects are further indicated by Figures A-4 to A-6. The graphs show that end point and average energies decrease almost linearly with absorber thickness, as does dose rate for small absorber thicknesses. End point energies decrease more rapidly than average energies. The greatest decrease, initially, is in the dose rate. However, at large absorber thicknesses, dose rate has the least rate of decrease. The present data are not good beyond those plotted, so suspected nonlinearities for end point and average energies near the maximum range of the beta particles cannot be demonstrated. An extension of the plots does not go to zero at the maximum range of the beta particles.

A nonlinear decrease of end-point and average energies with absorber thickness is expected near the maximum range of the betas, since all betas are then of low energy. At lower energies, the loss with thickness should increase more rapidly with decreasing energy. However, the average energies and end-point energies are not decreasing toward a common zero point. The end point energies, the average energy, and the dose should finally go to zero at the same absorber thickness. This region has not been sufficiently investigated to date.

The effect of a linear or nearly linear decrease of dose rate with absorber at small absorber thicknesses is that the TLDs should show a linear response over a short range, i.e., much less than the maximum range. This is consistent with an exponential model, since the initial portion of an exponential attenuation can be well approximated by a straight line. Table A-2 shows exponential absorption coefficients calculated from absorption data. The values are consistent with expected exponential attenuation coefficients for beta particles.

TABLE A-2. EFFECTIVE MASS ATTENUATION COEFFICIENT cm^2/gm UNITS[a]

Tl 204 at 20 cm	$K = 1.9 \times 10^{-2}$
Sr-Y-90 at 22.3 cm	$K = 3.2 \times 10^{-3}$
Sr-Y-90 and Tl 204	$K = 5.4 \times 10^{-3}$

a. Values were calculated using INEL Personnel Dosimeter Data.

Note that with the mixed beta sources, the range investigated (45-300 mg/cm^2) is below that of the weakest energy. If the range were greater than one of the betas, or a single beta emitter was in an extended source (i.e. a varying amount of absorber across the source), then a nonlinear response would be expected for part of the range. A properly responding dosimeter would need absorbers of varying thicknesses (at least three) in order to demonstrate and to enable calculation of any nonlinear decrease with depth. Present measurements indicate that neither a linear nor an exponential model is proper for a single nonextended beta source, but an exponential model may be the best approximation for mixed extended sources, as are encountered in a working environment. This needs to be further investigated.

APPENDIX B

CALIBRATION AND OPERATING PROCEDURES

APPENDIX B

CALIBRATION AND OPERATING PROCEDURES

The calibration of the INEL dosimetry system consisted of two separate but related efforts. The first task consisted of optimizing the instrumentation parameters that are associated with the dosimetry system. The second task was a performance evaluation of the dosimetry system using well-defined and calibrated beta and gamma sources.

The procedures used in optimizing the reader instrument parameters were based upon the experience gained after several years of development and operational work with this dosimetry system at the INEL.

A hot gas reader, Harshaw Model 2000D, is used to convert the thermoluminescence of the TLD chip to an electrical current by means of a photomultiplier tube. Preheated nitrogen gas of very high purity (less than 2 ppm oxygen and less than 1 ppm water) at 345^{o}C and at a flow rate of 60-65 cm^3/s was used in the reader to heat the TLD chips. These values were selected as being optimum, based upon the experience with this reader at the INEL. The photomultiplier tube was maintained at a constant 12^{o}C by using the water from a NESLAB Model RTE-4 refrigerated circulating bath. The photomultiplier tube operating voltage was chosen to maximize the signal-to-noise ratio. This ratio was determined by using the reference light of the reader as a constant and reproducible signal source and the dark current from the photomultiplier tube as a measurement of the noise. Data were compiled at fifty-volt increments from 500 volts to 1350 volts. The maximum signal-to-noise ratio of 9.9 was found at 1100 volts[a] (the data are shown in Figure B-1). At voltages greater than this value, the dark current increases rapidly and the dispersion of both

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a. Probably, 1100 v is too high, based on reduced tube life and the risk of "overdriving" the system in the unexpected case of a high exposure. Minimum decrease in signal-to-noise ratio at 600-700 v would make this lower voltage the voltage of choice.

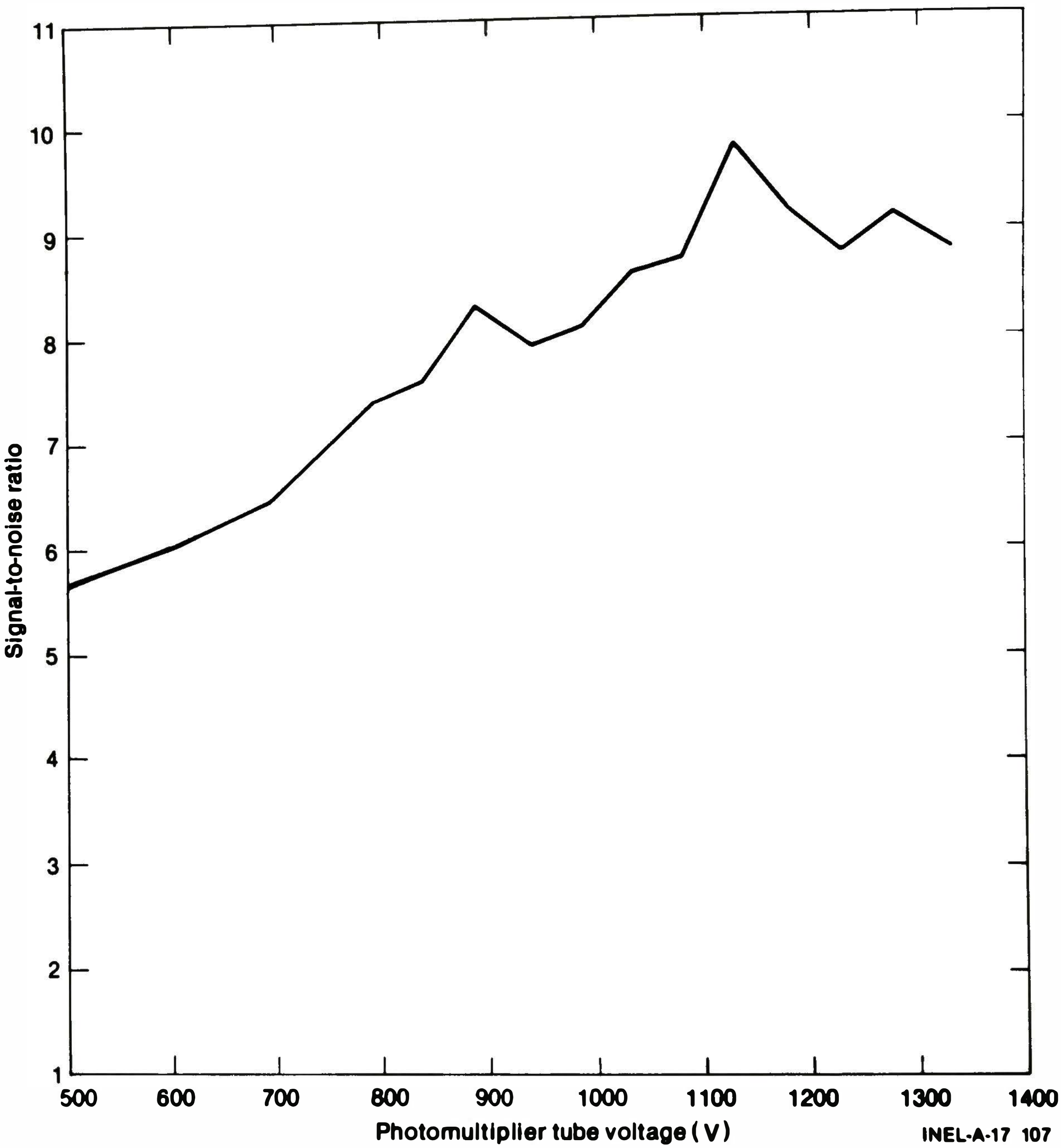

Figure B-1 Signal-to-noise ratio.

the reference signal and the dark current increase. An integrating picoammeter, Harshaw Model 2000B, was used to measure the current from the photomultiplier tube of the hot gas reader. The readout period during which the current is integrated was chosen as 10.0 seconds. This time period was chosen after an evaluation of glow curves revealed that a ten-second integrating period would include the entire thermoluminescence peak.

System linearity was examined to ensure that the nanocoulomb response was a linear function of TLD chip exposure. As shown in Figure B-2, this is the case in the range tested.

Once the equipment parameters were optimized, the TLD chip response to several exposing, annealing, and reading protocols were examined. This response check was necessary because the accepted protocol in use at the INEL involves a 24-hour delay between exposure and reading, followed by a 16-hour post-readout anneal at 85^{o}C. Since this prolonged delay between exposure and readout would not be acceptable for the recovery operations taking place at Three Mile Island Unit 2, a series of tests were done to see if the pre-readout delay procedure could be altered by using a smaller post- exposure delay combined with a pre-readout anneal. The experimental procedures are described as follows:

1. Cycling of 100 TLD-700 chips through the accepted INEL exposure, delay, readout, anneal protocol five times.

2. Dividing these TLD chips into five groups of twenty chips such that each group had approximately equal mean response to 300 mR Cs-137 and equal standard deviations. Each chip was individually identified and followed throughout this entire investigation.

3. Following the protocol scheduled in Table B-1:

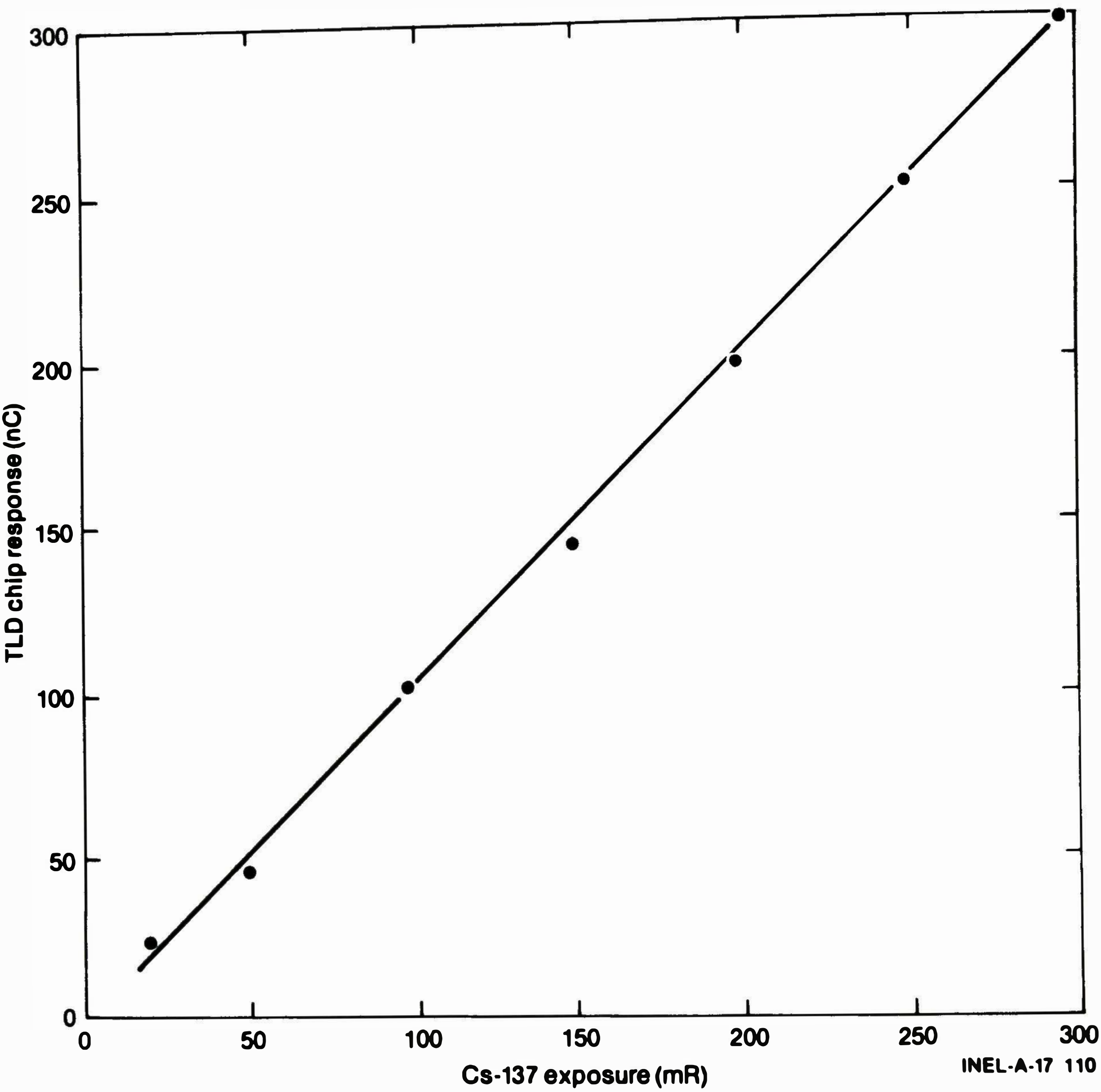

Figure B-2 Linearity of INEL system.

TABLE B-1. PROTOCOL FOR EXPERIMENTAL ANNEAL

Group	TLD Chip Numbers	Pre-Exposure Anneal	Exposure	Pre-Readout Anneal
A	1-20	85°C for 16 hours	300 mR ^{137}Cs	none-24 hour delay
B	21-40	85°C for 16 hours	300 mR ^{137}Cs	none-1 hour delay
C	41-60	85°C for 16 hours	300 mR ^{137}Cs	20 min at 100°C
D	61-80	85°C for 16 hours	300 Mr ^{137}Cs	10 min at 100°C
E	81-100	85°C for 16 hours	None	10 min at 100°C

The results are shown in Table B-2 and displayed in Figures B-3 through B-6:

TABLE B-2. RESULTS OF EXPERIMENTAL ANNEAL

Group	Initial % S.D.	Number of Measurements	Final Mean Reading of Group	Final % S.D.	Range of % S.D.
A	1.10	60	314.0	1.08	1.05-1.11
8	1.11	60	313.6	1.09	0.99-1.11
C	1.12	60	313.7	2.46	2.18-2.74
D	1.11	60	312.8	1.44	1.25-1.63
E	1.15	40	8.7	1.66	1.64-1.68

From these results, it was decided that with the oven available and other conditions, a pre-readout anneal increases the standard deviation in an unacceptable manner, even though the mean readings did not vary significantly. Further study was made to investigate more fully the effect of delaying the time between exposure and readout. These results are shown in Table B-3:

TABLE B-3. RESULTS OF EXPERIMENTAL ANNEAL AFTER DELAY BETWEEN EXPOSURE AND READOUT

Delay Period Between Exposure and Readout	Cs-137 Exposure	Number of Measurements	mR	Percent Standard Deviation
35 minutes	200 mR	20	230	4.03
1 hour	200 mR	20	206	1.38
3 hour	200 mR	20	205	1.53
5 hours	200 mR	20	221	1.39
10 hours	200 mR	20	224	1.39

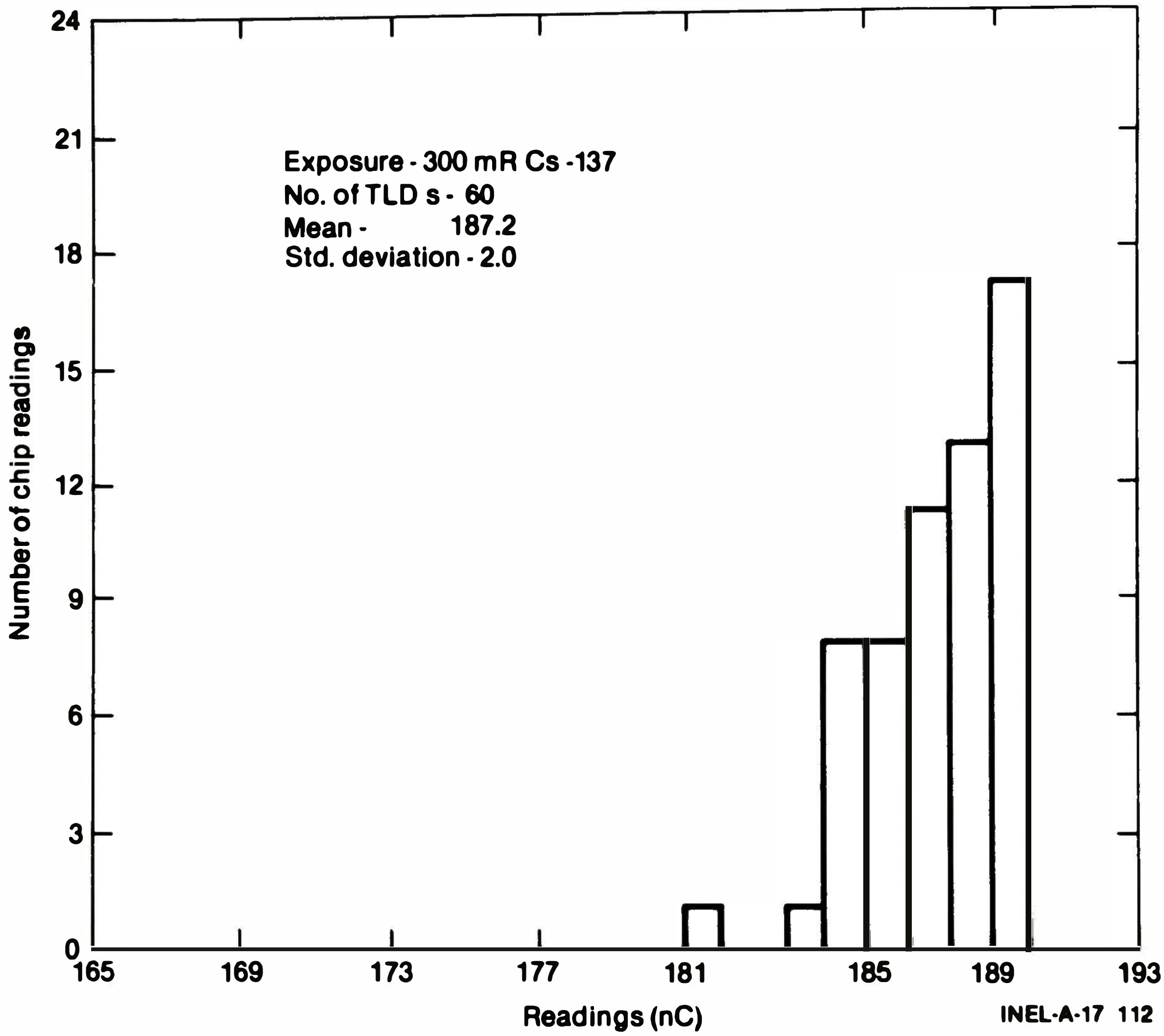

Figure B-3 Distribution of chip reading - Group A.

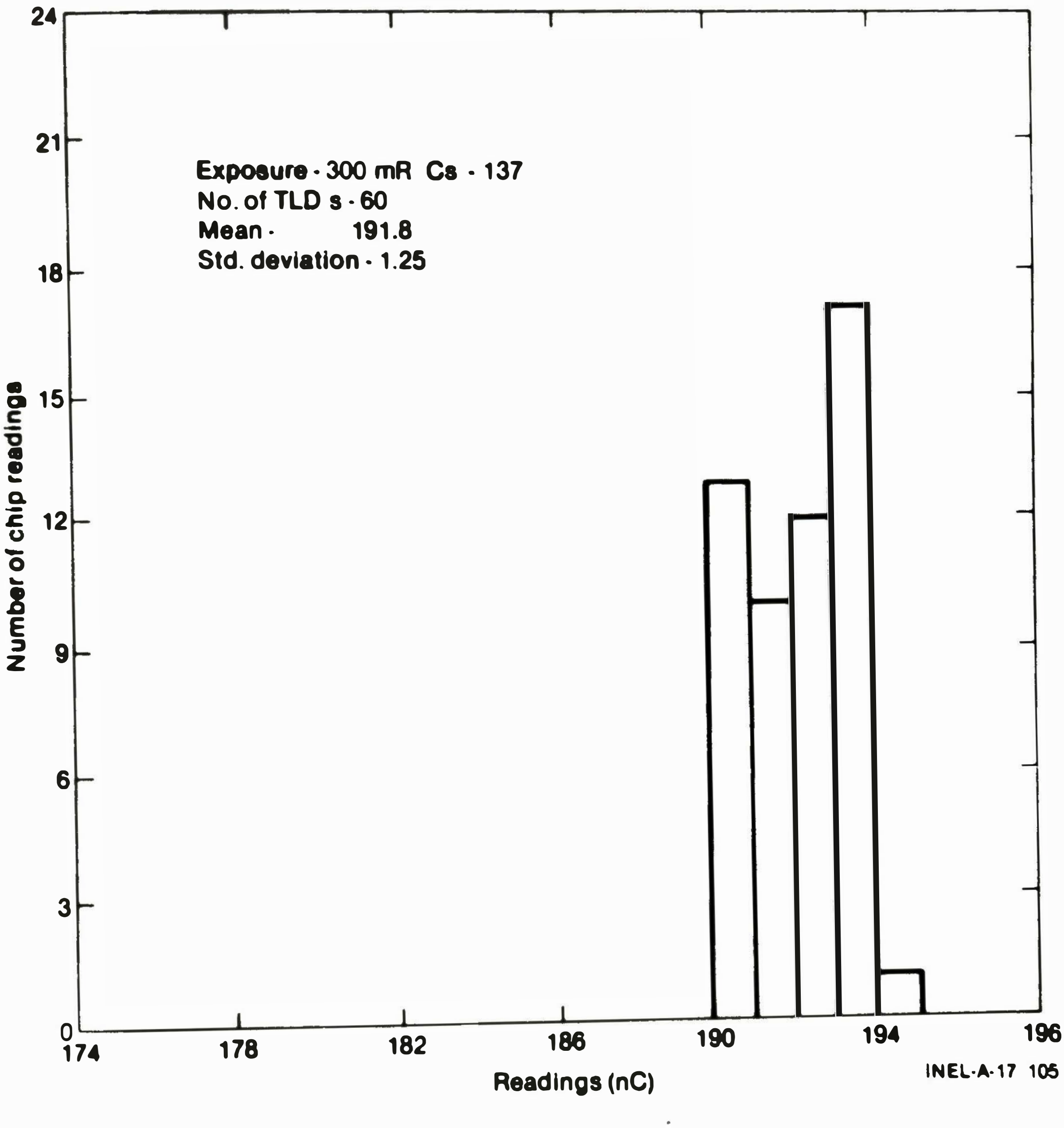

Figure B-4 Distribution of chip reading - Group B.

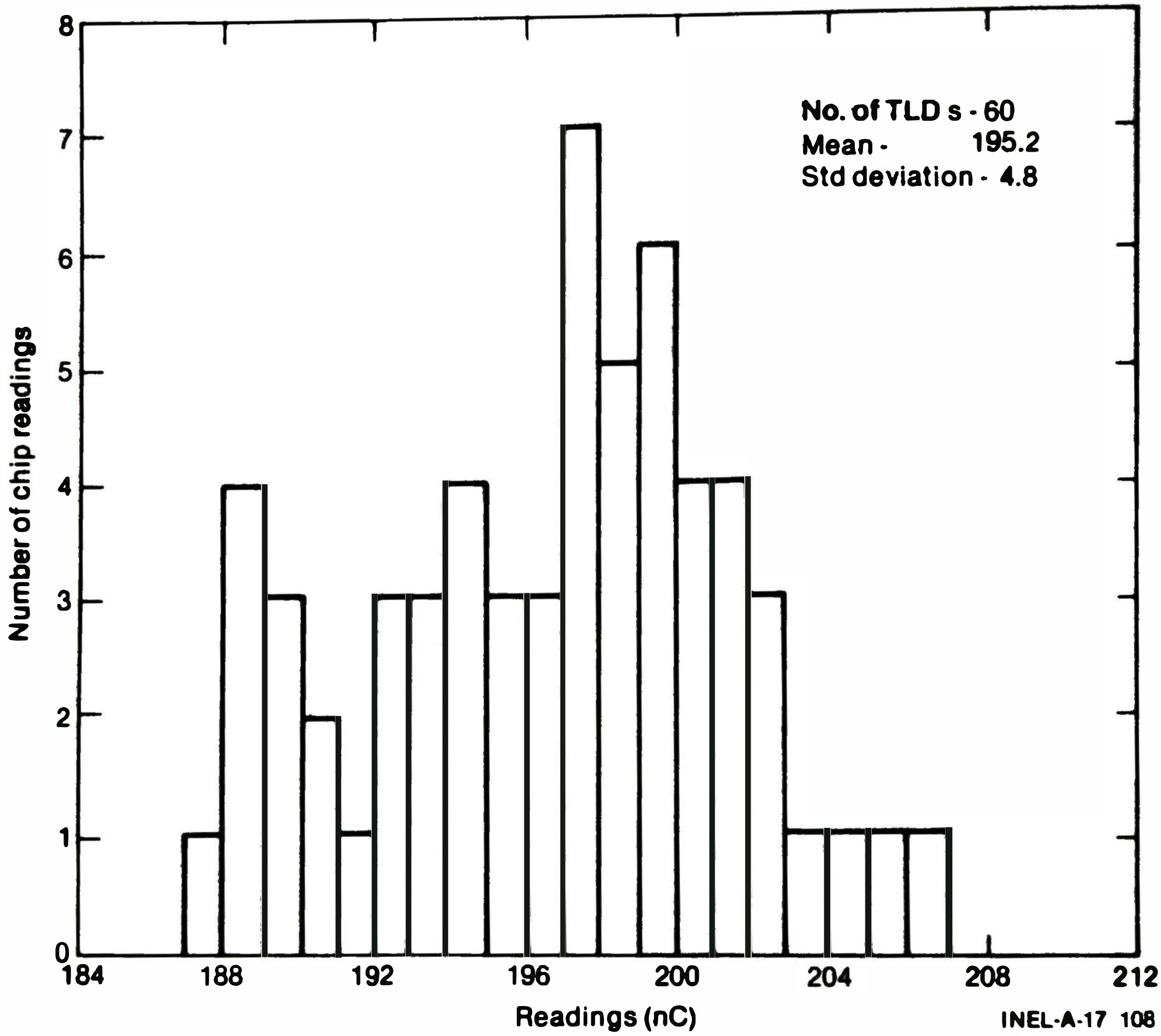

Figure B-5 Distribution of chip reading - Group C.

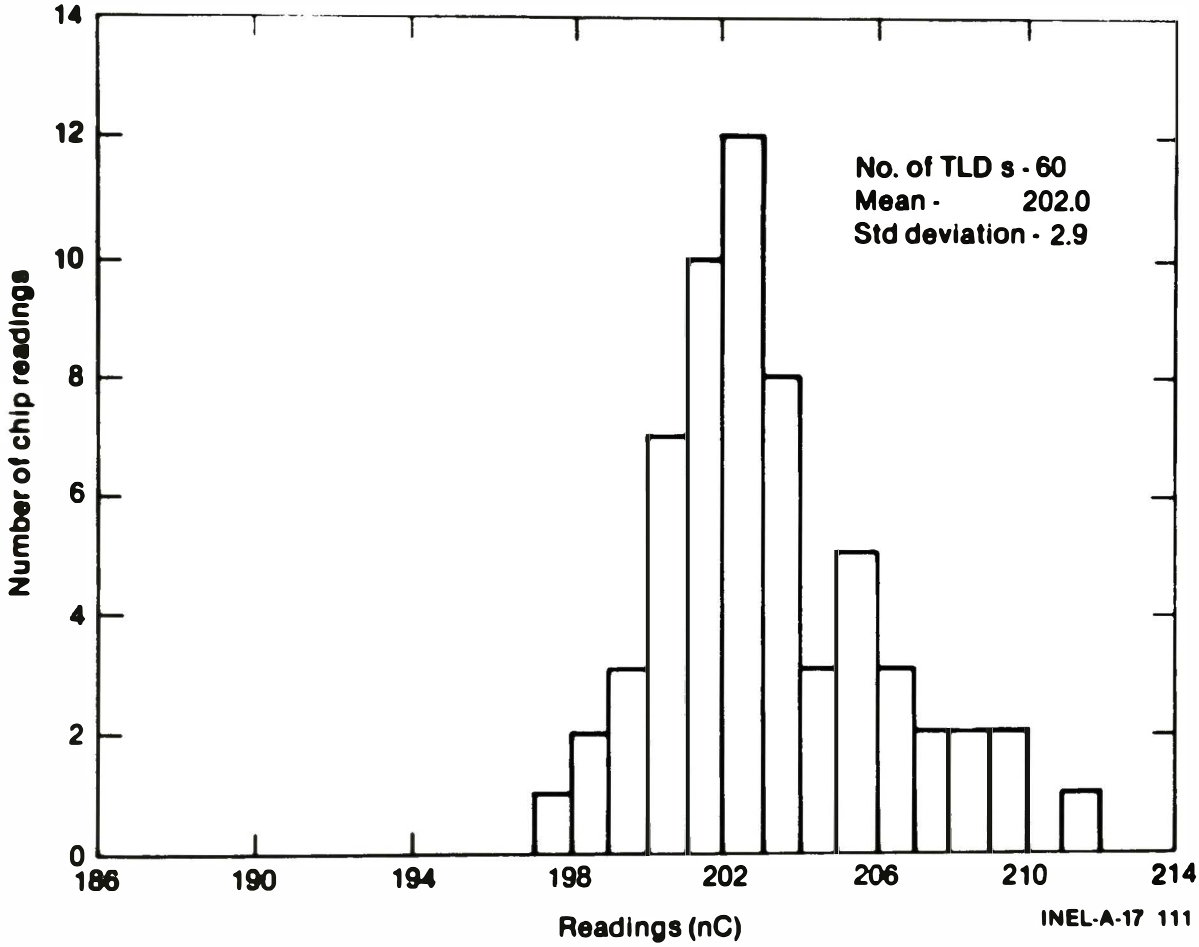

Figure B-6 Distribution of chip reading - Group D.

These data support the protocol of using an hour delay between exposure and readout. This essentially completed the work needed to calibrate and optimize the instrument parameters associated with the INEL dosimetry system. The work was completed within a month because it was based upon the experience gained at the INEL over the last several years.

After the system was calibrated, its performance was evaluated by exposing the dosimeters to well-defined and characterized sources. The gamma source used was 100 mCi of Cs-137 enclosed within a lead irradiator that includes a manually operated shutter. The beam emitting from the irradiater is essentially a 45^{0} cone. The exposure rate is approximately 100 mR/h at 54.7 cm. The exact exposures were measured using a Victoreen Condenser R-meter, Model 130, chamber #345. The meter was read on a Victoreen Model 570 electrometer. The INEL dosimeters to be exposed were attached to the front of a thin plastic sheet in such a way that the geometries could be repeated with each exposure. A few exposures were made at an exposure rate of 200 mR/h at a source-to-dosimeter distance of 38.7 cm. All exposures were corrected for temperature, pressure, probe correction factor, and electrometer correction factors. These correction factors were supplied from an NBS calibration.

The beta exposures were made in a plexiglass container that maintained repeatable geometries at several source-to-dosimeter distances. The exposure times used in these experiments were based upon dose rates supplied by NBS at the appropriate source-to-dosimeter distances. The actual dose rate used in the comparison was measured in the apparatus using a Victoreen extrapolation chamber with a Victoreen 500 electrometer. Refer to Appendix A for the details of source calibration. The measured dose rates for Tl-204 at 20.0 cm was 19.7 mRad/s at 7.0 mg/cm. The dose rate measured for the Sr/Y-90 point source at 22.3 cm was 0.79 mRad/s at 7.0 mg/cm. The Tl-204 source consisted of two rectangular metal sources, one with an overhanging lip so that the two sources overlap when mounted next to each other. The uniformity of the radiation field was measured at a source-to-TLD distance of 20.0 cm, using 100 TLD chips behind a thin lucite holder. The 100 TLD chips were distributed over an area of

80.0 cm^2. The response of these TLD chips are matched to a standard deviation of less than 2.0% on exposure to 300 mR Cs-137. The nanocoulomb readings of the TLD chips on exposure to the Tl-204 showed a variation of 480 percent. There is a 52% difference between the dose rate at the center of the field and the dose rate 4.0 cm from the center but on the same horizontal plane. For this reason, the Tl-204 exposures were done one dosimeter at a time with the dosimeter placed at the same place in the holder for each exposure. The Sr/Y-90 source was essentially a point source and these radiation field variation considerations were assumed to be unnecessary. The exposure schedule used to establish the dosimeter performance is shown in Figure B-7 below. Because of the probability of high energy beta doses and high beta/gamma dose ratios during the TMI recovery operations, the schedule includes beta/gamma ratios of 10/1 and 3/1. The mixed radiation fields used in this schedule will also give beta energy spectra representative of the potential energies encountered during TMI Unit 2 recovery.

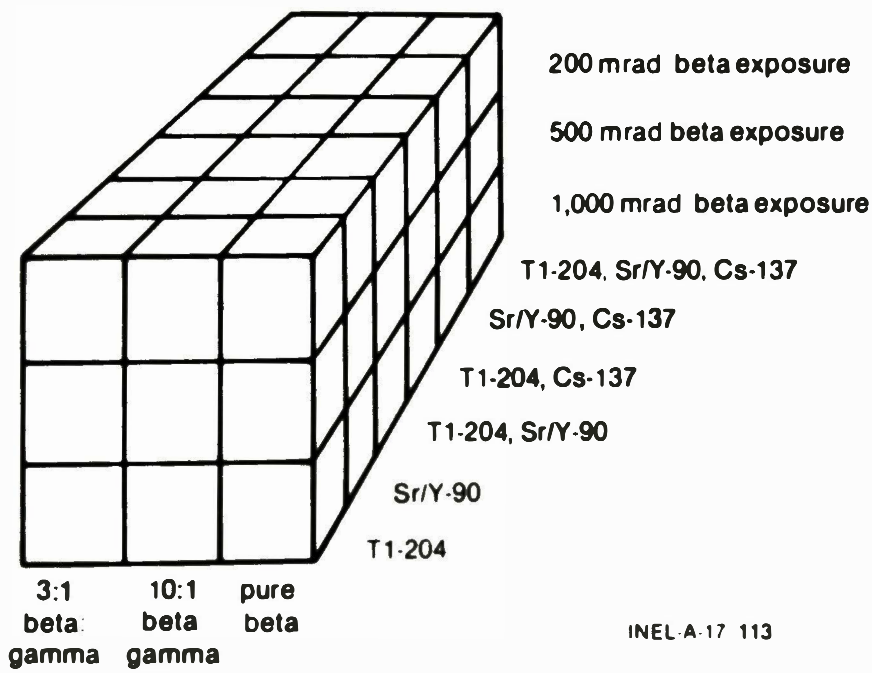

Figure B-7. Exposure matrix for INEL dosimeter.

This matrix contains fifty-four cells where five badges were exposed per cell to the source(s). Three additional badges were used to establish a gamma calibration factor during each experiment, and two badges retained as controls. The TLD chips were read an hour after the exposure. Care was taken to ensure that the chips were loaded into the reader so that the TLD chip surface facing the radiation source during the exposures was facing "up" on the reader.[a] The TLD chips were always taken out and loaded into the dosimeters under subdued light and handled by vacuum tweezers. The TLD chips were cleaned on a weekly basis, using gentle agitation in analytical grade trichloroethylene. Before each reading of the TLD chips, a hot-gas automatic recorder check sheet was completed. This allowed the experimenter to detect a change in instrument settings or a drift in the dark current, reference light signal, zero setting, or other instrument parameter. The output from the picoammeter was recorded by a Model 6150 Digetec printer and a MFE Model M-12D single-channel chart recorder.

The dose calculations were made using the algorithm developed by T. F. Gesell, et al., at the INEL.[1] This algorithm computes the integrated dose from 5-10 mg/cm by calculating an effective mass attenuation coefficient, k, derived from the output of the two shallow chips, C_1 and C_2. TLD chip C_1 is shielded by 9.2 mg/cm of tissue equivalent material, while C_2 is shielded by 45.3 mg/cm.

$$\frac{C_1}{C_2} = \exp\,(45.3 - 9.2)\,(k) \quad \text{or}$$

$$k = 0.028 \ln \frac{C_1}{C_2} \,.$$

Then, a geometry factor, F, is calculated, which relates the dose between 5-10 mg/cm to the dose measured from TLD chip C_1 which is between 9.2 and 249.2 mg/cm^2. This factor is defined as follows:

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a. This amount of care in a routine field system is not considered necessary, and will probably introduce no more than .2-.3% variability.

$$F = \frac{\frac{1}{k(b-a)}\left(e^{-ka} - e^{-kb}\right)}{\frac{1}{kT}\left(e^{-t_1 k} - e^{-(t_1 + T)k}\right)}$$

where

T	=	the thickness of a TLD chip
a	=	5 mg/cm^2
b	=	10 mg/cm^9

In this algorithm, which is designed to measure the average dose between 5 and 10 mg/cm^2, certain boundary conditions have been set upon the geometry factor F. If the ratio between TLD chip C_1 and C_2 is less than 1.2, then the beta radiation is considered to be of high energy and very penetrating, and F is set at 1.6. When this ratio is greater than or equal to ten, the beta radiation is considered to be of low energy and F is set equal to 16. The beta dose is then equal to FCG, where C is the corrected TLD chip #1 reading and G is the individual TLD chip gamma calibration factor. The gamma calibration factor (mR/nc) is calculated by exposing the TLD chip to a known Cs-137 exposure of approximately 200 mR and measuring the nanocoulomb response of the TLD chip. These measurements were taken every other day during the first month of the matrix test, until confidence in the consistency of the gamma calibration factor was assured. After that, it was checked every three or four days. It has been demonstrated that TLD chips that have absorbed equal doses from either gamma or beta radiation will provide equal light output.[2] Thus, the use of this factor in computing a nonpenetrating dose is valid.

The results of the matrix experiments are shown in Tables B-4 through B-8. The delivered doses shown in the tables are based upon the extrapolation chamber data adjusted to an average tissue dose between 5-10 mg/cm for the nonpenetrating doses and the tissue dose under 1,000 mg/cm for the penetrating dose as discussed in Appendix A.

The mean observed-to-delivered dose ratio for pure and mixed beta sources was 1.07, with a standard deviation of three percent for the nonpenetrating dose. With a beta-gamma radiation dose rate ratio of approximately ten the mean observed-to-delivered dose ratio was 1.02, with a standard deviation of 5.6 percent for the nonpenetrating dose. When the beta-gamma radiation dose rate ratio was about three, the mean observed-to-delivered dose ratio was 0.96, with a standard deviation of 8.7 percent for the nonpenetrating dose. The ratio of the observed-to-delivered dose for the penetrating dose was 1.02, with a standard deviation of ten percent.

TABLE B-4. RESPONSE OF THE INEL DOSIMETER TO BETA RADIATION
(The indicated errors are two standard deviations of the mean.)

Isotope	Dose Delivered (mrad)	Ratio of Observed to Delivered Dose
^{90}Sr-Y	246	0.94 ± 0.03
	617	0.94 ± 0.03
	1236	0.93 ± 0.03
^{204}Tl	230	1.13 ± 0.06
	574	1.14 ± 0.07
	1147	1.21 ± 0.09
	1119	1.24 ± 0.09
^{204}Tl, ^{90}Sr-Y	212	.93 ± 0.14
	424	.91 ± 0.04
	1060	1.00 ± 0.03

TABLE B-5. RESPONSE OF THE INEL DOSIMETER TO A COMBINED BETA-GAMMA RADIATION FIELD

Isotopes	Doses Delivered Nonpenetrating (mRad)	Doses Delivered Penetrating (mRem)	Ratio of Observed-to-Delivered Dose Nonpenetrating (mRad)	Ratio of Observed-to-Delivered Dose Penetrating (mRem)
Tl-204 Cs-137	242	19.3	1.03 ± 0.04	1.17 ± 0.10
	574	40.4	1.04 ± 0.10	1.03 ± 0.07
	1151	81.1	1.19 ± 0.13	1.13 ± 0.04
	150	45.3	0.98 ± 0.40	1.03 ± 0.11
	419	113.4	0.90 ± 0.08	0.93 ± 0.07
	839	197.6	1.05 ± 0.19	1.00 ± 0.03
Sr/Y-90, Cs-137	250	20.0	0.98 ± 0.04	1.01 ± 0.20
	625	45.6	1.01 ± 0.03	0.95 ± 0.05
	1250	91.2	0.99 ± 0.05	0.99 ± 0.11
	185	41.8	1.03 ± 0.02	1.10 ± 0.12
	464	107.1	1.11 ± 0.17	1.06 ± 0.12
	929	236.4	1.00 ± 0.22	1.06 ± 0.18
Sr/Y-90, Tl-204, Cs-137	235	20.0	1.09 ± 0.23	1.23 ± 0.10
	530	39.5	0.91 ± 0.03	0.87 ± 0.08
	885	213.6	0.88 ± 0.02	1.05 ± 0.10
	589	47.0	0.98 ± 0.36	0.98 ± 0.07
	176	43.5	0.80 ± 0.19	0.91 ± 0.07
	442	106.8	0.96 ± 0.22	0.88 ± 0.10
	885	213.6	0.92 ± 0.22	0.92 ± 0.18

TABLE B-5. RESPONSE OF THE INEL DOSIMETER TO A COMBINED BETA-GAMMA RADIATION FIELD

Isotopes	Doses Delivered: Nonpenetrating (mrad)	Doses Delivered: Penetrating (mrem)	Ratio of Observed-to-Delivered Dose: Nonpenetrating (mrad)	Ratio of Observed-to-Delivered Dose: Penetrating (mrem)
Tl-204 Cs-137	242	19.3	1.03 ± 0.04	1.17 ± 0.10
	574	40.4	1.04 ± 0.10	1.03 ± 0.07
	1151	81.1	1.19 ± 0.13	1.13 ± 0.04
	150	45.3	0.98 ± 0.40	1.03 ± 0.11
	419	113.4	0.90 ± 0.08	0.93 ± 0.07
	839	197.6	1.05 ± 0.19	1.00 ± 0.03
Sr/Y-90, Cs-137	250	20.0	0.98 ± 0.04	1.01 ± 0.20
	625	45.6	1.01 ± 0.03	0.95 ± 0.05
	1250	91.2	0.99 ± 0.05	0.99 ± 0.11
	185	41.8	1.03 ± 0.02	1.10 ± 0.12
	464	107.1	1.11 ± 0.17	1.06 ± 0.12
	929	236.4	1.00 ± 0.22	1.06 ± 0.18
Sr/Y-90, Tl-204, Cs-137	235	20.0	1.09 ± 0.23	1.23 ± 0.10
	530	39.5	0.91 ± 0.03	0.87 ± 0.08
	885	213.6	0.88 ± 0.02	1.05 ± 0.10
	589	47.0	0.98 ± 0.36	0.98 ± 0.07
	176	43.5	0.80 ± 0.19	0.91 ± 0.07
	442	106.8	0.96 ± 0.22	0.88 ± 0.10
	885	213.6	0.92 ± 0.22	0.92 ± 0.18

TABLE B-6. PERCENT STANDARD DEVIATION OF THE BETA DOSE
Beta Source 90 Sr-Y
Gamma Source 137 Cs

Gamma/Beta Ratio	Total Beta Dose Delivered 200 mrads	500 mrads	1,000 mrads
0.0	3.0	3.2	3.3
0.1	1.8	5.1	8.2
0.3	2.4	8.7	10.8

TABLE B-7. PERCENT STANDARD DEVIATION OF THE BETA DOSE
Beta Source 204 Tl
Gamma Source 137 Cs

Gamma/Beta Ratio	Total Beta Dose Delivered 200 mrads	500 mrads	1,000 mrads
0.0	7.0	3.3	4.7
0.1	21.5	5.1	6.9
0.3	20.3	4.2	9.5

TABLE B-8. PERCENT STANDARD DEVIATION OF THE BETA DOSE
Beta Source 204 Tl and 90 Sr-Y
Gamma Source 137 Cs

Gamma/Beta Ratio	Total Beta Dose Delivered 200 mrads	500 mrads	1,000 mrads
0.0	7.0	1.5	1.1
0.1	15.2	1.7	5.8
0.3	9.5	10.6	10.6

REFERENCES

B-1. T. Gesell, D. Jones, et al., "A Personnel -Dosimetry Method for Reducing Energy Dependence," IDO-12090, 1979.

B-2. J. Lasky and P. Moran, "Thermoluminescence Response of LiF (TLD-100) to 20 ev to 30 Kev Electrons," Proceedings the 5th International Conference on Luminescence Dosimetry.

APPENDIX C

STATEMENT OF DOSIMETER LIMITATIONS

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STATEMENT OF DOSIMETER LIMITATIONS

Though the limitations of the INEL dosimeter have been discussed throughout the report, it is desirable to formulate a summary statement in the interest of maintaining perspective. The INEL dosimeter represents the state of the art in mixed-field beta dosimetry, and will provide good data within the inherent limitations of beta dosimetry in general. The science of beta dosimetry is not at all sophisticated at this point, and possibilities for significant improvement exist. More research in this area is clearly required.

The INEL badge utilizes comparatively thick TLD dosimeters. This necessitates formulation of an algorithm to evaluate an effective energy, which is necessary to choose an effective calibration factor, as it is a function of energy. The relatively thick TLD detector and "open window" absorber thickness also places limits on the maximum energy that can be "seen" by the badge, and affects the lower limit of sensitivity of beta-related dose in high gamma-beta ratio fields. Again, though this dosimeter represents the best currently available, it has limitations that can and should be reduced through further development.

Data acquired at the INEL during the review of this report indicate an overresponse to x-rays and to pure thermal neutron spectra. These observations indicate that the current prototype will require further refinements in these areas.

It should be stated, in addition, that the current 2-chip badge with a maximum of 270mg/cm^2 filter has specific limitations. Nearly any dosimeter could be an improvement for TMI recovery operations; for example, a 2-chip badge with 5-10 mg/cm^2 and approximately 600 to 1000 mg/cm^2 filters would be a major upgrade. The other multifilter dosimeters tested and compared could probably be modified and calibrated to provide response equivalent to the INEL badge.

APPENDIX O

CURRENT STATUS OF THE INEL PROTOTYPE SYSTEM

APPENDIX D

CURRENT STATUS OF THE INEL PROTOTYPE SYSTEM

The INEL prototype system in service at TMI can be used to manually process a limited number of badges. The system consists of the following equipment:

	ITEM	SOURCE
1.	Harshaw Reader Model 2111D	GPU Purchased
2.	Hashaw Automatic Integrating Picoameter Model 2111B	GPU Purchased
3.	Digital Recorder Model 6111	GPU Purchased
4.	MFE Strip Chart Recorder	GPU Purchased
5.	NESLAB Refrigerated Circulating Bath	GPU Purchased
6.	N_2 Tanbis Model RTE-4 and Regulator	GPU Purchased
7.	Thermalyne Furnace Model 11511	GPU Purchased
8.	2 Annealing Trays	Borrowed from RESL
9.	1 KNF Neuberger Vacuum Pump	GPU Purchased
10.	TNP Cassette Holders	GPU Purchased
11.	134 LiF TLD Chips	Borrowed from RESL
12.	25 INEL Badges	Borrowed from RESL
13.	INEL Badge Back Remover	Borrowed from RESL

Though the prototype system can produce technically accurate results, manual processing of dosimeters is inconvenient, requires extreme care in TLD handling, and potentially limits the number of badges that can be processed. Equipment has been developed that will make the system semiautomatic and provide comparative processing convenience, although still not as convenient as other "card" semiautomatic systems. The equipment required to provide the semiautomated system is listed as follows:

1. Harshaw TL Hot Gas Reader Model 2111D - a RESL modification allowing acceptance of whole badges without manually removing TLDs from badge

2. Blue M Oven - for accurate annealing of TLD and whole badges in large numbers at a time

3. Harshaw Irradiator - for use in the readout cycle to provide individual calibration of each TLD during cycle, providing increased accuracy and sensitivity.

APPENDIX E

FUTURE PROJECTS

APPENDIX E

FUTURE PROJECTS

In order to implement an operational INEL system, the following projects require completion:

- o Order Badges and TLDs
- o Order an automatic decapper
- o Modify the TLD reader
- o Calibrate reader and dosimeter
- o Develop computer processing program(s) compatible with current record keeping computer
- o Train operators in the new system.

An indispensable part of any new system or procedure is the training necessary to ensure effective implementation. The need to upgrade the personnel dosimetry and field survey capability at TMI-2 is now well known and accepted. The upgraded system will need to be understood by those responsible for the day-to-day use; and thus training is essential.

The reader used with the INEL system is a hot gas (N_2) reader and requires its own annealing procedure and careful accounting of each TLD. The analyses of the data require computer processing of an algorithm with specific extreme condition limits. This must also be well understood by the operating technicians.

A detailed training program should be presented by system experts, as the system is received, set up, and calibrated.

Portable survey instruments have been calibrated more thoroughly for beta response since the accident, and the best instruments for the intended service have been chosen. However, the techniques of relating field surveys to reliable estimates of the personnel dose as recorded by the dosimeter are an art and require considerable skill and understanding of both systems. Training is necessary to improve the ability to predict personnel dose from field survey information. This will ensure dose accumulation at ALARA levels, since nonproductive transit time in the radiation fields is held to a minimum.

As previously indicated, there is a critical, industry-wide need to develop improved instrumentation, beta dosimetry techniques, and dosimeters. As these systems are developed and implemented, additional training will be necessary.

If an alternate system is chosen in preference to the INEL system for operational reasons of convenience, etc., there will be a significant effort required to provide a system with reliable and accurate response.

- o Evaluate the intended system response to mixed beta-gamma fields
- o Modify the badge design as required
- o Order equipment and badges
- o Carefully calibrate the system and develop calculational techniques
- o Develop computer programs compatible with the current record keeping computer system
- o Train operators of new system.