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Environmental Thermoluminescent Dosimetry Measurements at the WIPP Site, 1976 - 1985

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Abstract

In 1975, the U.S. Energy Research and Development Administration began evaluating a site in southeastern New Mexico for the possible construction and operation of a Waste Isolation Pilot Plant. The purpose of the facility was to test and demonstrate the operational and technical principles of a permanent repository in bedded salt for ERDA-generated transuranic radioactive waste. An extensive preoperational environmental study program to document the region's meteorology, geology, hydrology, flora and fauna, existing air and water quality, and background radiation was undertaken by Sandia National Laboratories. The purpose of this document is to report the final results of environmental thermoluminescent dosimeter measurements performed from January 1976 through December 1985. These final results were obtained by reevaluating the quarterly raw data using a uniform analysis procedure.

Acknowledgments

The author wishes to thank the following Sandia personnel for their contributions to this work:

Jim Metcalf for his efforts in selecting the WIPP test locations and for performing the quarterly exchanges;

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Contents

Figures

Tables

Environmental Thermoluminescent Dosimetry Measurements at the WIPP Site, 1976 – 1985

1. Introduction

In 1975 Sandia National Laboratories, Albuquerque (SNLA) at the request of the Energy Research and Development Administration (ERDA), now the U.S. Department of Energy (DOE), began an extensive preoperational environmental study program in southeastern New Mexico in anticipation of locating a Waste Isolation Pilot Plant (WIPP) Site there. The study consisted of documenting the meteorology, geology, hydrology, flora and fauna, existing air and water quality, and background radiation. The results of the preoperational study were meant to provide baseline values against which the results of future studies could be compared. This report documents the final results of the environmental thermoluminescent dosimeter (TLD) measurements performed from January 1976 through December 1985.

1.1 Monitoring Background Radiation

Thermoluminescent dosimeters (TLDs) were used to monitor the existing environmental background radiation at the WIPP Site. TLDs at selected WIPP Site locations were exchanged and evaluated on a quarterly basis during the ten-year study. The TLDs were prepared and evaluated at the Environment, Safety, and Health Department Dosimetry Laboratory at SNLA.

1.2 Uniform Analysis Testing Procedures

A protocol of assumptions, handling, and readout procedures was established at the beginning of the WIPP study and was followed throughout the study. Observations and critical dates are documented in a record book and in each quarter's data sheets. Any deviations from protocol were recorded and are identified in this report. Preliminary WIPP TLD results were obtained using a variety of statistical analysis procedures that were published early in the study. This early quarterly raw data has now been reevaluated using a uniform analysis procedure; the results from the latest procedure are documented in this present work.

1.3 Problems Caused by Distance

The field measurements in the WIPP study were complicated by the significant distance of the WIPP Site from the Dosimetry Laboratory. The distance made it necessary to use storage shields in both Carlsbad and Albuquerque. The distance also influenced the length of the exchange period. A short exchange period could have resulted in an increased uncertainty due to potential transit exposure. However, a long exchange period would have resulted in a loss of background fluctuation information. Thus, a quarterly exchange period was selected as a reasonable compromise.

1.4 Measuring Radiation Through the Batch Calibration Method

In general terms, a batch calibration method was used in evaluating the WIPP environmental TLDs. The TLD ribbons were annealed as a single batch at the beginning of each period; TLDs selected at random were exposed for the batch calibration midway through the exchange period; all TLDs, both field and calibration, were read as a batch at the end of each period.

2. TLD Field Station Location

The TLD Program began in January 1976 with TLDs initially placed at three field stations:

A. ERDA 6 Drill Site

B. AEC 7 Drill Site

C. AEC 8 Drill Site.

By January 1978, four more field stations were added to the program. They were:

D. Badger Drill Site (added in the third quarter of 1976)

E. ERDA 9 Drill Site (added in the third quarter of 1976)

F. Meteorology Station (added in the third quarter of 1977)

G. WIPP 11 Drill Site (added in the first quarter of 1978).

The criteria used for selecting monitoring stations were: 1) coverage of the area selected for the possible use of the WIPP Site, and 2) the accessibility for exchanging dosimetry materials. The areas selected were limited to those areas for which SNL had a Bureau of Land Management use permit. See Figure 1 for the approximate locations of the TLD field stations at the WIPP Site.

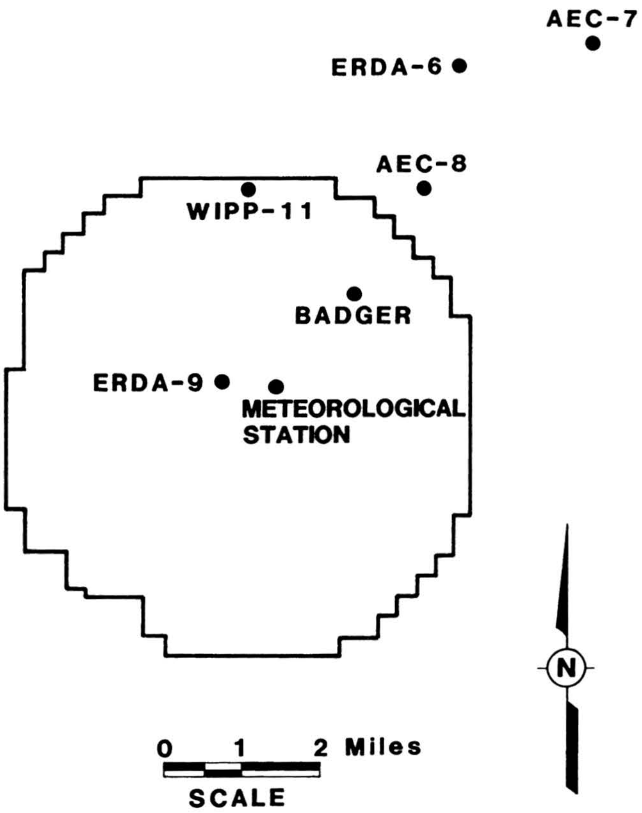

Figure 1. Sandia National Laboratories Dosimetry Stations at the WIPP Site

3. Program Description

3.1 Dosimeter Description

Harshaw LiF high sensitivity ribbons measuring ⅛″ × ⅛″ × 0.035″ were the TLD material used throughout the WIPP study. The dosimeters were used only for environmental monitoring and were cycled to ensure uniform use over the lifetime of the material.

Due to loss and damage, it was necessary to use two batches of TLD ribbons over the ten-year period covered by the WIPP study. Harshaw LiF TLD-100 ribbons were used from the first quarter 1976 through the second quarter 1982; Harshaw LiF TLD-700 ribbons were used from the third quarter 1982 through the fourth quarter 1985. The ribbons were purchased from Harshaw/Filtrol Partnership, 6801 Cochran Rd., Solon, OH 44139.

3.2 Dosimeter Package Description

In preparing the dosimeters for field use, sets of five TLD ribbons were first wrapped in a thin aluminum foil or placed in a thin black polyethylene bag; these precautions protected the dosimeters from ultraviolet radiation. For convenient handling and identification, the TLDs were then placed in numbered plastic vials 7/16 in in diameter and 11/16 in high. At the appropriate time, these vials were transported to the WIPP Site where they were placed in a waterproof plastic bottle and then in a thin-walled (0.035 in) aluminum tube. The aluminum tube was designed to protect the dosimeter package from animals, to make it easy to find, and to support the dosimeter, which was placed approximately one meter above the ground. See Figures 2 and 3.

Figure 2. Example of Dosimeter Package and Field Station Used in WIPP Study

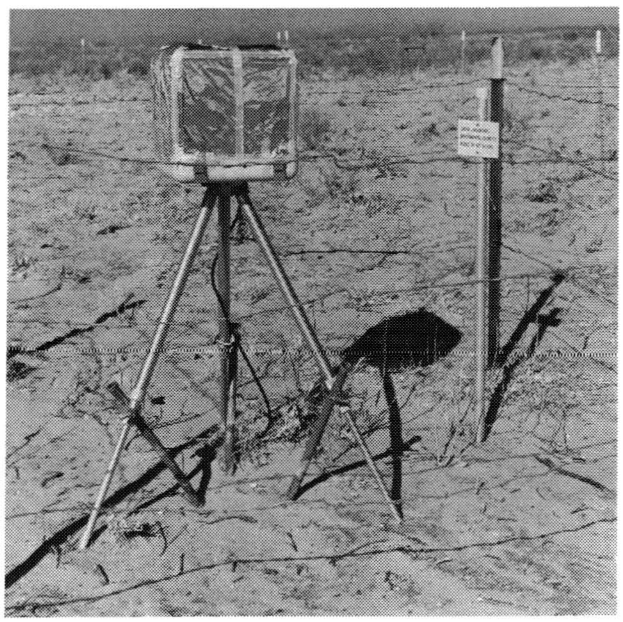

Figure 3. TLD Field Station and PIC Monitoring System at the WIPP Meteorology Station

3.3 Equipment Description

TLD Readers

Over the ten years of the study, two TLD readers were used to evaluate the TLDs: 1) An Eberline Model TLR–5 Manual TLD Reader was used from the first quarter 1976 through the third quarter 1980. It was purchased from the Eberline Instrument Company, P.O. Box 2108, Santa Fe, New Mexico, 85501. 2) A Harshaw Model 2000 Manual TLD Reader was used from the fourth quarter 1980 through the fourth quarter 1985. This model was purchased from the Harshaw/Filtrol Partnership, 6801 Cochran Rd., Solon, OH 44139.

TLD Anneal Furnace

A Thermolyne Type 10500 furnace with solid state controller was purchased from the Thermolyne Corporation, Dubuque, IA 52001.

Ultrasonic Cleaners

Various units were used during the WIPP study.

Lead Storage Shields

Two similar lead storage shields were constructed in January 1976 at the beginning of the WIPP study. They were located: 1) in the basement of Building 869, Sandia Technical Area 1, Albuquerque, NM; and 2) in the Sandia WIPP Office, Carlsbad, NM. These storage shields were made of lead brick from the same batch and have 4-in-thick walls. Through the years, circumstances have required that the shields be moved. Generally, these moves have occurred within the original room; however, in March 1979 it was necessary to move the Carlsbad shield to another building when the Carlsbad Sandia office was relocated. In all cases, however, the shields were reconstructed to original plan specifications.

3.4 Procedure Description

The procedures used in performing TLD environmental radiation background measurements in the WIPP study are described below. A data sheet for each quarter was kept to record dosimeter numbers, calibration points, and critical dates (i.e., anneal, storage, transit, field, calibration and read dates).

TLD Cleaning

The TLDs required for each quarterly exchange were placed in a beaker that contained 1,1,1 trichloroethane and run in the ultrasonic cleaner for approximately 15 minutes. They were then removed from the solution and allowed to dry.

TLD Anneal

The cleaned TLDs were annealed in one group. They were placed in a 3 ½ inch petri dish and annealed at 400°C for one hour. After annealing, the petri dish was placed on a lightweight metal grate to allow slow and uniform cooling to room temperature.

Dosimeter Assembly

The data sheet for each quarterly exchange specified the number of field and calibration dosimeters to be assembled. These dosimeters were protected from ultraviolet radiation by wrapping the TLD ribbons in a thin aluminum foil or by placing the TLDs in a black polyethylene bag. The TLDs were then placed in numbered plastic vials. Finally, the field and calibration dosimeters were placed in a lead shield.

The field dosimeters, including the trip control dosimeter, remained in the lead shield until they were picked up for transportation to the WIPP Site. The date on which they were removed was recorded on the data sheet and in the WIPP log book. The calibration dosimeters, including the calibration and control dosimeters, remained in the Albuquerque lead shield throughout the exchange cycle, except for a very short time at midcycle when they were exposed for calibration.

Dosimeter Transit and Exchange

The trip control dosimeter was kept with the field dosimeters at all times during transportation between Albuquerque and the Sandia WIPP office in Carlsbad. Upon arrival at the Carlsbad office, the trip control for the new exchange group was placed in a lead shield where it would remain throughout the exchange period. The trip control for the group currently in the field was removed from the shield and accompanied the field dosimeters during the exchange. Following the exchange, the recovered field dosimeters (plus the associated trip control) were returned to the Albuquerque lead shield.

The date and time of the dosimeter placement and recovery at each location, along with the corresponding dosimeter number, were also recorded in the WIPP log book. These dates constitute the field cycle dates for that exchange period. If a delay was likely, either before the field dosimeters could be exchanged or before they could be returned to Albuquerque, they were kept in the lead shield at the Sandia WIPP office in the interim.

TLD Calibration Exposures

The quarterly TLD calibration exposures for WIPP background radiation measurements were performed at the SNL Gamma Radiation Standards Facility; this facility is maintained by the Health Instrumentation Division 3313. Over the ten-year period covered by this study, two different sources were used to provide TLD calibration. The sources were: 1) a ^{60}Co source located in Building 868; this source was used during the first quarter 1976 through the second quarter 1983; 2) a ^{137}Cs source located in Building 818; this source was used during the third quarter 1983 through the fourth quarter 1985.

The facilities have maintained calibration traceability to the National Bureau of Standards (NBS) through the use of NBS-certified R-Chambers for both ^{60}Co and ^{137}Cs. See Appendix A for information concerning the uncertainties associated with the gamma calibrations.

Calibration exposures were performed each quarter on a group of TLDs randomly chosen from the batch annealed for the quarterly exchange. These exposures were made at several levels over the range expected (10 – 80 mR) for the field dosimeters. Multiple exposure levels were used to reduce the chance of making a calibration error and to verify that the instrument response was linear over the exposure range.

Calibration exposures were performed midway through the field cycle. This procedure was followed to offset any fading that might occur in the field TLD signal over the exposure period. The assumption was that the exposure rate and the TLD fade rate were relatively uniform over the exposure period. The calibration date was recorded on the data sheet.

TLD Readout

At evaluation time, the WIPP field and calibration TLDs were removed from the lead shield and taken to the radiation dosimetry office. The date of the removal/read was recorded on the data sheet.

Before the TLD readout was started, the instrument operating parameters of read time, temperature, heat rate, and regions of interest were verified and recorded. Also verified were the instrument reference light and dark current readings and the flow of nitrogen gas.

The operating parameters for the Eberline TLR – 5 were:

Preheat: 7 sec at 165°C

Readout: 15 sec at 250°C

The operating parameters for the Harshaw – 2000 were:

Heat time/rate: 25 sec at 10°C/sec

Region of interest: 175°C – 250°C

Readout results for field TLDs and calibration TLDs were recorded on the readout data sheet. The data sheet information contained all the information required for determining the exposure rate and the measurement error for each of the field locations.

4. Determining Field Exposure Rates and Measurement Errors

The final analysis of the WIPP TLD data for the entire study was performed using personal computer (PC) software that allowed the systematic and uniform processing of data for each location. The transit and storage exposures were subtracted from the field results. The uncertainty values include the propagation of measurement errors resulting from the readout of the TLDs.

4.1 Calibration Response and Uncertainty

Calibration of the TLD readout equipment consisted of determining the reader response to the readout of TLDs exposed to known exposure levels. The average and variance for each set of TLD data were determined. The net calibration exposure responses were also determined by subtracting the average calibration control response. A regression analysis was performed to test the data for linearity and zero intercept. If the test failed, calibration data were plotted to determine why the test failed. Upon successful completion of the calibration analysis, the instrument response values necessary for analysis of the field data were printed and saved in a computer file.

4.2 Net Field Response and Uncertainty

The net TLD field response is obtained when the responses due to transit, storage, and inherent system background are subtracted from the field TLD response.

Trip Control and Calibration Control Dosimeter Responses

The exposure received by the field dosimeters during transit to the field was determined by comparing the trip control and calibration control dosimeter responses. The trip control dosimeter accompanied the field dosimeters during the trip to Carlsbad and was stored in the Carlsbad shield until the return trip to Albuquerque. The calibration control dosimeter was stored in the Albuquerque shield for the entire period. The assumption necessary in making the comparison was that the exposure rates in both shields were equal. Therefore, if a statistically significant difference was found between the trip control and the calibration control, it was assumed to be the result of an exposure during transit. See Appendix A for more information.

Field Dosimeter Storage Response

This response was due to exposure received while the field dosimeters were in storage in the Albuquerque shield before and after the field cycle. This response was determined by evaluating the calibration control TLDs that were kept in the shield throughout the exchange period. The amount of field dosimeter storage response is determined by the share of total time it spent in the shield.

System Background Response

The system background response was taken to be the average reading of the reread (or second read) of the calibration TLDs. This value includes the instrument dark current plus the effect of heating an unexposed TLD.

Data Analysis

Finally, the net field results were compared to the calibration values to yield the field exposure rate in microroentgen per hour (μR/hr). Random errors were statistically combined to determine the total uncertainty at the 95% confidence level. See Appendix B for a more complete explanation of the method used in the data analysis.

5. Results

See Table 1 for the final results of the preoperational TLD monitoring program at the WIPP Site. The results represent the average exposure rates in μR/hr due to penetrating background radiation for each measurement period. Exposure rates and measurement errors for the entire study were determined using personal computer (PC) software that allowed the systematic and uniform processing of data for each location; see Figure 4 for a summary of this data.

The uncertainty values reported in Table 1 provide 95% confidence limits on the averages, and are derived from the TLD measurements. In keeping with standard practice, errors of a systematic nature (such as energy and angular dependence, fading and timing measurements) are not included in the reported uncertainty values. For additional information regarding systematic errors, see Appendix A.

5.1 Comparison of TLD Results

A comparison of TLD measurements with quarterly averaged pressurized ionization chamber (PIC) measurements is made in Table 2.

A Reuter-Stokes Model RSS−111 Area Monitoring System was used to measure and record, on a continuous basis, the environmental background levels at the WIPP Meteorology Station for the period January 1977 through December 1979. The system was purchased from Reuter-Stokes Inc., 18530 South Miles Parkway, Cleveland, OH 44128.

The data from this study are reported in other Sandia reports, listed in this report as References 1−6. The summary data from these reports were compared with the TLD data in this report.

5.2 Discussion of Results

The results presented in Table 1 and Figure 4 show expected fluctuations between periods with measurement errors generally less than 10% of the average exposure rate. Examination of the results also shows an apparent annual cycle in the quarterly exposure rates. The exposure rates for both the second and third quarters were lower than for both the first and fourth quarters in 72% of the cases for all years and locations. In an additional 23% of the cases, the exposure rates for the second and third quarters were lower than either the first quarter or the fourth quarter.

This apparent annual cycle could be the result of seasonal changes in soil moisture content and temperature. Moisture content can affect the transport of radon and radon daughters in the soil, whereas higher summer temperatures may increase the fade of the stored TLD signal. Either one or both of these could cause the lower readings for the summer months.

A comparison of the TLD and PIC results presented in Table 2, when averaged over the six quarters for which there was data for both methods, shows good agreement between the two monitoring methods. The average results are TLD 7.4 ± 0.8 μR/hr, and PIC 7.8 ± 0.3 μR/hr.

Table 1. Penetrating Environmental Radiation Measured by Thermoluminescent Dosimeters at Seven Locations at the WIPP Site. The exposure rates are given in μR/hr, the measurement errors are given at the 95% confidence level.

Location: Badger Drill Site

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1976	NDP	NDP	NDA	8.4 ±1.0[a]
1977	9.3 ±1.8[a]	7.8 ±0.8	12.0 ±3.3	9.5 ±1.0
1978	7.0 ±0.9	7.0 ±0.5	NDA	6.9 ±1.2
1979	DNR	NDA	7.6 ±0.5	8.5 ±0.4
1980	7.8 ±0.7	5.7 ±0.4	6.2 ±0.4	7.4 ±0.5
1981	7.2 ±1.2	7.0 ±0.4	7.0 ±0.5	7.0 ±0.3[a]
1982	6.5 ±0.5[a]	6.3 ±0.6[a]	6.1 ±0.4[a]	7.5 ±0.8[a]
1983	6.7 ±0.7[a]	6.9 ±0.8[a]	7.0 ±0.5[a]	8.1 ±0.5[a]
1984	6.9 ±5.0[a,b]	6.3 ±0.5[a,b]	6.9 ±0.6[a]	7.2 ±0.6[a]
1985	7.0 ±0.5[a]	5.5 ±0.9	5.5 ±1.6	8.8 ±4.0

Location: Meteorology Station

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1976	NDP	NDP	NDP	NDP
1977	NDP	NDP	8.5 ±3.0	8.5 ±0.9
1978	7.4 ±1.0	6.6 ±0.3	NDA	7.7 ±1.2
1979	6.4 ±0.2	NDA	7.5 ±0.5	9.1 ±0.6
1980	7.8 ±0.5	5.8 ±0.4	6.4 ±0.3	7.4 ±0.5
1981	7.0 ±0.8	7.1 ±0.4	6.9 ±0.5	6.7 ±0.4[a]
1982	6.3 ±0.4[a]	6.3 ±0.3[a]	5.7 ±0.4[a]	7.2 ±0.5[a]
1983	6.9 ±0.7[a]	6.0 ±0.8[a]	6.7 ±0.5[a]	7.2 ±0.5[a]
1984	6.5 ±1.0[a,b]	6.2 ±0.4[a,b]	6.2 ±0.5[a]	7.1 ±0.5[a]
1985	7.5 ±1.2[a]	4.5 ±0.7	5.8 ±1.2	4.0 ±2.8

NDP No dosimetry performed. Dosimetry at this location not started until later date.

DNR Dosimeter not recovered. Dosimeter or dosimeter station missing or otherwise not recovered this period.

NDA No data available. No data available for this period due to difficulty with readout or calibration.

a System background data not available for this period. Value used in exposure calculation was average of adjacent quarters. The reported error does not include the additional systematic uncertainty.

b Calibration data not available for this period. Calibration used in exposure calculation is from the 4th quarter 1983. The reported error does not include the additional systematic uncertainty.

(continued)

Table 1 (continued)

Location: ERDA 6 Drill Site

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1976	8.7 ±1.8[a]	5.8 ±1.0[a]	NDA	7.6 ±0.9[a]
1977	9.9 ±1.4[a]	8.0 ±0.9	11.2 ±4.3	9.6 ±1.0
1978	7.7 ±0.9	7.4 ±0.2	NDA	6.1 ±1.2
1979	6.2 ±0.4	NDA	8.0 ±-0.5	8.9 ±0.4
1980	8.4 ±0.5	5.7 ±0.5	6.6 ±0.3	7.8 ±0.6
1981	7.6 ±1.1	DNR	7.0 ±-0.5	6.9 ±0.7[a]
1982	6.4 ±0.5[a]	6.3 ±0.6[a]	5.6 ±0.5[a]	6.5 ±0.8[a]
1983	6.3 ±0.6[a]	6.1 ±0.6[a]	6.4 ±0.6[a]	7.0 ±0.4[a]
1984	6.6 ±0.6[a,b]	6.0 ±0.3[a,b]	6.4 ±0.5[a]	6.4 ±0.5[a]
1985	6.2 ±0.9[a]	4.6 ±0.4	5.9 ±0.9	8.6 ±4.2

Location: AEC 7 Drill Site

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1976	9.5 ±2.0[a]	6.5 ±0.9[a]	NDA	9.7 ±0.9[a]
1977	9.5 ±1.4[a]	9.2 ±0.9	9.9 ±3.0	10.2 ±1.0
1978	7.7 ±0.8	7.9 ±0.3	NDA	7.2 ±1.2
1979	DNR	NDA	7.9 ±0.3	9.3 ±0.8
1980	8.0 ±0.6	6.1 ±0.5	7.1 ±0.3	7.2 ±0.6
1981	8.0 ±0.7	7.4 ±0.4	7.4 ±0.5	7.7 ±0.5[a]
1982	6.3 ±0.4[a]	6.4 ±0.5[a]	6.5 ±0.6[a]	7.8 ±0.5[a]
1983	7.2 ±0.5[a]	6.9 ±0.6[a]	7.3 ±0.4[a]	8.5 ±1.3[a]
1984	7.0 ±1.2[a,b]	6.3 ±0.4[a,b]	6.9 ±0.4[a]	7.2 ±0.5[a]
1985	6.7 ±0.7[a]	6.2 ±0.8	6.8 ±0.9	7.9 ±1.8

NDP No dosimetry performed. Dosimetry at this location not started until later date.

DNR Dosimeter not recovered. Dosimeter or dosimeter station missing or otherwise not recovered this period.

NDA No data available. No data available for this period due to difficulty with readout or calibration.

a System background data not available for this period. Value used in exposure calculation was average of adjacent quarters. The reported error does not include the additional systematic uncertainty.

b Calibration data not available for this period. Calibration used in exposure calculation is from the 4th quarter 1983. The reported error does not include the additional systematic uncertainty.

(continued)

Table 1 (continued)

Location: AEC 8 Drill Site

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1976	10.0 ±1.8[a]	6.0 ±1.0[a]	NDA	8.7 ±1.0[a]
1977	9.3 ±1.7[a]	8.4 ±0.7	8.9 ±3.0	9.5 ±1.0
1978	6.9 ±0.9	7.3 ±0.4	NDA	6.0 ±1.2
1979	6.2 ±0.3	NDA	8.1 ±1.0	9.3 ±0.7
1980	8.3 ±0.5	6.3 ±0.7	7.0 ±0.6	7.1 ±0.5
1981	7.8 ±0.8	7.2 ±0.4	7.1 ±0.5	7.5 ±0.5[a]
1982	7.0 ±0.5[a]	6.4 ±0.6[a]	6.0 ±0.6[a]	7.3 ±0.3[a]
1983	7.0 ±0.4[a]	6.7 ±0.7[a]	7.9 ±0.6[a]	7.7 ±0.7[a]
1984	7.1 ±0.3[a,b]	6.8 ±0.5[a,b]	7.2 ±0.6[a]	7.3 ±0.5[a]
1985	7.3 ±0.5[a]	4.9 ±0.7	4.6 ±1.4	8.3 ±1.3

Location: ERDA 9 Drill Site

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1976	NDP	NDP	NDA	8.8 ±1.0[a]
1977	10.4 ±1.4[a]	7.7 ±0.7	7.5 ±3.0	8.6 ±1.0[a]
1978	7.4 ±0.9	6.9 ±0.2	NDA	5.9 ±1.2
1979	7.1 ±0.6	NDA	7.6 ±0.5	9.0 ±0.4
1980	8.6 ±0.6	5.6 ±0.6	6.6 ±0.6	7.5 ±0.4
1981	7.5 ±0.7	6.6 ±0.6	6.9 ±0.5	8.1 ±0.5[a]
1982	6.5 ±0.4[a]	6.4 ±0.6[a]	6.1 ±0.5[a]	7.3 ±0.5[a]
1983	6.6 ±0.9[a]	6.4 ±0.9[a]	6.8 ±0.4[a]	7.4 ±0.4[a]
1984	6.9 ±0.5[a,b]	6.2 ±0.3[a,b]	6.5 ±0.5[a,b]	6.6 ±0.6[a]
1985	7.7 ±0.5[a]	4.8 ±0.4	5.9 ±0.9	8.8 ±1.2

NDP No dosimetry performed. Dosimetry at this location not started until later date.

DNR Dosimeter not recovered. Dosimeter or dosimeter station missing or otherwise not recovered this period.

NDA No data available. No data available for this period due to difficulty with readout or calibration.

a System background data not available for this period. Value used in exposure calculation was average of adjacent quarters. The reported error does not include the additional systematic uncertainty.

b Calibration data not available for this period. Calibration used in exposure calculation is from the 4th quarter 1983. The reported error does not include the additional systematic uncertainty.

(continued)

Table 1 (concluded)

Location: WIPP 11 Drill Site

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1976	NDP	NDP	NDP	NDP
1977	NDP	NDP	NDP	NDP
1978	7.2 ±0.9	6.9 ±0.2	NDA	5.8 ±1.4
1979	6.3 ±0.3	NDA	7.0 ±0.7	8.0 ±0.6
1980	7.6 ±0.6	5.4 ±0.4	6.3 ±0.3	7.2 ±0.3
1981	6.9 ±0.7	6.6 ±1.0	6.7 ±0.4	6.7 ±0.9[a]
1982	5.9 ±0.4[a]	6.0 ±0.5[a]	5.7 ±0.6[a]	7.4 ±0.9[a]
1983	6.5 ±0.6[a]	6.3 ±0.6[a]	6.6 ±0.4[a]	7.1 ±0.9[a]
1984	7.2 ±0.5[a,b]	6.8 ±0.6[a,b]	6.3 ±0.7[a]	7.3 ±0.5[a]
1985	7.7 ±0.6[a]	5.1 ±0.6	3.2 ±2.3	9.0 ±1.8

NDP No dosimetry performed. Dosimetry at this location not started until later date.

DNR Dosimeter not recovered. Dosimeter or dosimeter station missing or otherwise not recovered this period.

NDA No data available. No data available for this period due to difficulty with readout or calibration.

a System background data not available for this period. Value used in exposure calculation was average of adjacent quarters. The reported error does not include the additional systematic uncertainty.

b Calibration data not available for this period. Calibration used in exposure calculation is from the 4th quarter 1983. The reported error does not include the additional systematic uncertainty.

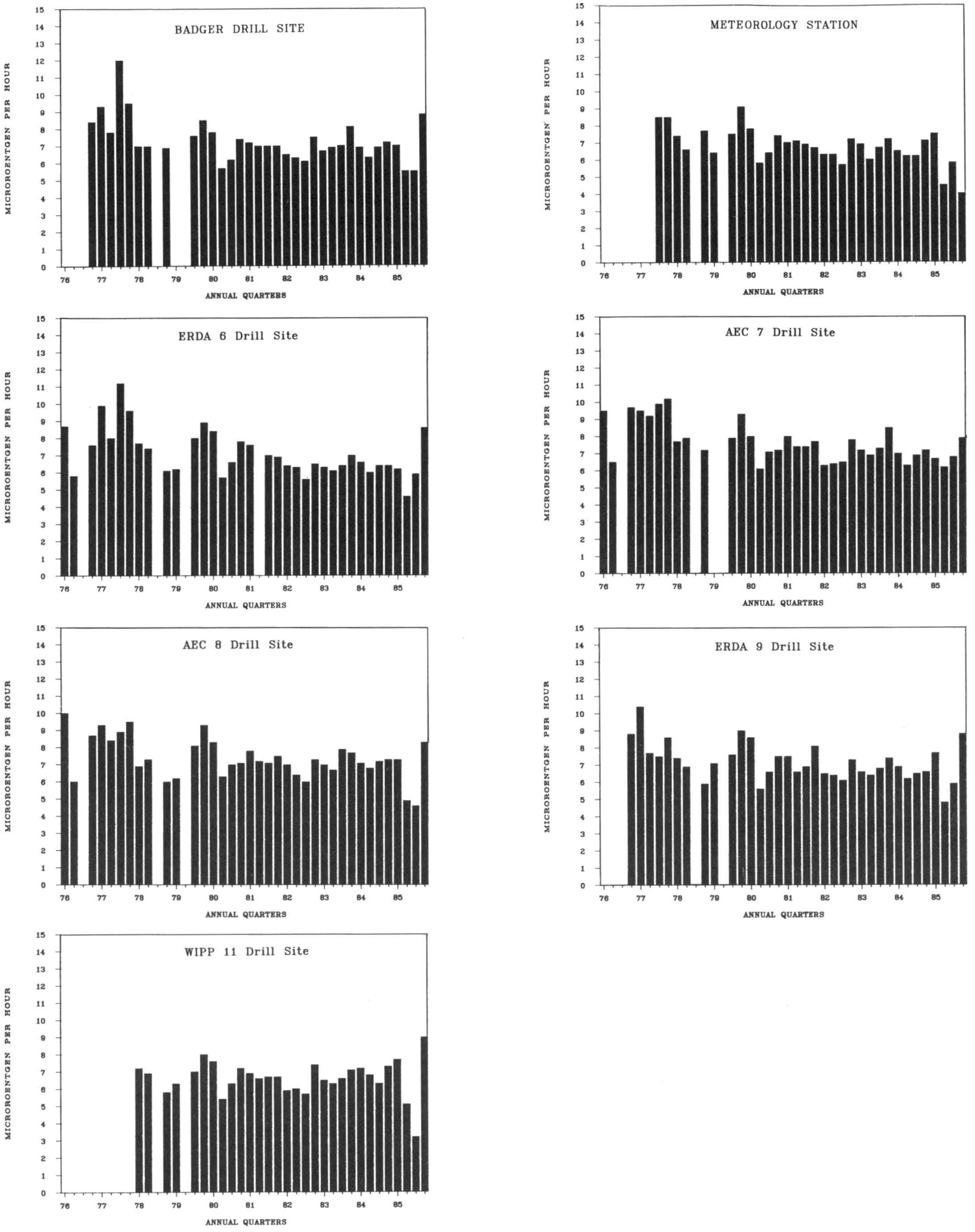

Figure 4. Annual Quarterly Radiation Background at the WIPP Site. (Measurements made using thermoluminescent dosimeters)

Table 2. TLD and PIC Results for the WIPP Meteorology Station 1977 Through 1979. The exposure rates are in μR/hr, the measurement errors are given at the 95% confidence level. Measurement errors for the PIC were derived from daily averages.

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1977				
TLD	NDP	NDP	8.5 ±3.0	8.5 ±0.9
PIC	8.8 ±0.09	NDA	NDA	8.1 ±0.05
1978				
TLD	7.4 ±1.0	6.6 ±0.3	NDA	7.7 ±1.0
PIC	8.0 ±0.06	7.7 ±0.03	7.7 ±0.06	7.9 ±0.07
1979				
TLD	6.4 ±0.2	NDA	7.5 ±0.5	9.1 ±0.6
PIC	7.8 ±0.05	7.4 ±0.03	7.3 ±0.05	NDA

NDP No dosimetry performed. Dosimetry at this location not started until later date.

NDA No data available for this period due to difficulty with readout or calibration.

References

[1]L. P. Pocalujka, E. Babij, and H. W. Church, *1979c: Meteorological Data Quarterly Report, WIPP Site: Eddy County, New Mexico, Winter Quarter, December 1976 February 1977,* SAND79-7042. Albuquerque: Sandia National Laboratories, 1979.

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[3]L. P. Pocalujka, E. Babij, P. A. Catizone, and H. W. Church, *1980b: Meteorological Data Quarterly Report, WIPP Site: Eddy County, New Mexico, Summer Quarter, June - August 1977,* SAND80-7107. Abuquerque: Sandia National Laboratories, 1980.

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[6]L. P. Pocalujka, E. Babij, P. A. Catizone, and H. W. Church, *Final Meterological and Air Quality Data Report, WIPP Site: Eddy County, New Mexico, March 1978 - February 1980,* SAND81-7052. Albuquerque: Sandia National Laboratories, 1981.

APPENDIX A

Analysis of TLD Systematic Errors

Purpose

The purpose of this appendix is to identify and assess those systematic errors associated with the WIPP Environmental TLD Program that have an impact on the accuracy of the field exposure estimates. The errors reported with the field exposure estimates in this study reflect only the precision or uncertainty of the TLD measurements.

Error Assessment

Both the assessment of measurement accuracy in environmental monitoring and a method for assessing total errors have been reported by G. de Planque and T. F. Gesell.[1] A similar method has been used to determine the total systematic error associated with the WIPP Environmental TLD Program. Systematic errors in the WIPP Program have been assessed in:

1. Tests as prescribed in ANSI N545 (1975)
2. Field measurements
3. Results from the literature
4. Estimates based on WIPP records

To make the assessed errors more meaningful, the error was calculated as a percentage of a typical field exposure rate of 8.0 μR/hr. The errors reported are at one confidence interval.

Errors Associated With Time

TLD Calibration Exposure Times

There are two timing errors associated with the TLD calibration exposure:

- The accuracy of the timing device (t_{c1})
- The repeatability of the exposure times (t_{c2})

The accuracy of the timing device is specified by the manufacturer to be within $\pm$ (0.015% $\pm$ 0.1 sec). For the standard 180 sec calibration exposure time, the error is $\pm$ 0.07%. SNLA's Electrical Standards Division has tested the timer and verified that it meets the manufacturer's timing specifications.

The repeatability of the exposure time is a measure of the difference between the actual exposure time and the specified exposure time, the difference being due to the placement and removal of the dosimeter over the calibration source. The repeatability of the exposure time (t_{c2}) is estimated to be within $\pm$1 sec of the standard 180 sec calibration exposure time, giving an error of $\pm$ 0.56%.

Field Cycle Length

The error associated with the length of the field cycle (t_f) results from the uncertainty involved in defining the exact beginning and end of the field cycle. At the beginning and the end of the field cycle, there is a short period when the field dosimeters and the trip control are separated, and the trip control is not in the storage shield. It has been assumed that the two dosimeters have had identical exposure during this time and that the error is a timing error. The record book shows that the dosimeters were always exchanged during the same work day. Assuming an average field cycle of 2190 hrs, the error of (t_f) is estimated to be $\pm$ 4 hrs or $\pm$ 0.18%.

Shield Storage Time

The error associated with the shield storage time (t_s) results from the uncertainty of knowing the exact time of placement and removal of the field dosimeters from the storage shield, both before and after the field cycle. The record books show that the average storage time (t_s) was approximately 172 hours, and that the average length of the total exchange cycle (t_t), i.e. the TLD preparation-to-TLD readout was approximately 2350 hours long. If it is assumed that there was an uncertainty of $\pm$4 hours for each of four shield transactions, then the error of t_s is estimated to 172 $\pm$ 16 hrs or $\pm$ 9.3%. However, the error associated with the shield storage time has a reduced effect on the field exposure estimate because:

1. The storage time is a fraction of the total exchange cycle, and

2. The shield exposure rate (R_s) is a fraction of the field exposure rate (R_f). Therefore, the

$$\text{fractional time} = \frac{t_s}{t_t} = \frac{172}{2350}\text{hrs} = 0.073,$$

and the fractional exposure

$$\text{rate} = \frac{R_s}{R_f} = \frac{2.4}{8.0}\mu\text{R/h-r} = 0.030.$$

Thus, the effective storage error (t_s) is estimated to be 9.3% × 0.073 × 0.30 = ±0.20%.

Errors Associated With TLD Response

TLD Directional Dependence

The test for directional dependence (d) of the ⅛ × ⅛ × 0.035 TLD chips was performed using the method prescribed in ANSI Standard N545–1975. Two sets of TLD chips were simultaneously exposed to 20 mR of ^{137}Cs radiation. Set One was exposed in the standard, flat calibration orientation. Set Two was exposed on edge.

The response averaged over both orientations differs from the response of the standard calibration orientation by −1.4 ± 1.6%. Thus, the error associated with directional dependence (d) is estimated to be −1.4 ± 1.6%.

TLD Self Irradiation

The error due to TLD exposure resulting from self-irradiation (X_s) can be ignored if the exposures in the field and calibration TLDs are identical. However, in the WIPP Program, the exposure due to self-irradiation of the calibration TLDs is compensated for by subtracting the calibration control. The field TLD has no comparable compensation, and any exposure due to self-irradiation is included in the final results.

To determine the exposure rate due to self-irradiation, a group of 942 LiF TLD chips was analyzed for photon radiation for 60,000 sec on a high purity germanium detector. Spectran-F software (purchased from Canberra Industries, Inc., One State Street, Meridan, CO 06450) was used to perform qualitative and quantitative analysis of the resulting spectrum. The analysis indicated a net ^{40}K activity concentration of 0.08 ± 0.06 pCi/gm.

Converting the ^{40}K activity concentration to exposure, yields a beta dose rate of 0.07798 ± 0.05785 µrad/hr and a gamma exposure rate of 0.000198 ± 0.000147 µR/hr. Assuming that 1 rad is equivalent to 1 R, the total exposure rate due to self-irradiation is 0.078 ± 0.058 µR/hr. Using the typical field exposure rate of 8.0 µR/hr, the percentage error due to self-irradiation (X_s) is 1.0 ± 0.73.

TLD Energy Response

The TLD photon energy response (e) was determined by folding together the TLD photon energy dependence and the photon energy distribution of a typical field spectrum.

The TLD photon energy dependence was determined using the method prescribed in ANSI Standard N545–1975. Sets of TLDs packaged with a wall thickness equivalent to the field holder were exposed to photons at nine energy levels, from 20 keV to 1333 keV. The greatest energy dependence for the LiF TLDs was found for photon energies less than 200 keV. The TLD energy response relative to the standard ^{137}Cs calibration ranged from an over-response of 29% at 70 keV, to an under-response of 65% at 20 keV.

The environmental photon energy distribution used for this test was provided by H. L. Beck,[2] who found that 90% of the exposure rate from a typical field spectrum is from photons having energy greater than 100 keV.

Summing the product of the TLD photon energy response and the environmental photon energy distribution for seven energy groups below 2 MeV, and dividing by the sum of the environmental photon energy distribution, yields a TLD photon energy response (e) of −0.9 ± 5.5%.

TLD Fade

The test for TLD fade (f) was performed at room temperature using the method prescribed in ANSI Standard N545–1975. A set of TLDs were annealed and placed at a location having a relatively constant exposure rate. At 45 days, a second set of TLDs were annealed and placed at the same location. At 90 days, both sets of TLDs were removed and evaluated.

The comparison of the 90-day response to two times the 45-day response yields a fade value of 0.2 ± 1.1%. Thus, the error associated with TLD fade is estimated to be 0.2 ± 1.1%.

Errors Associated With Calibration Standard

This section considers errors associated with the SNL Gamma Radiation Standards (C) used to provide the quarterly calibration exposures for the WIPP TLDs.

In the SNL facility, radiation sources used for calibration exposures are positioned by computer-controlled motors to provide the desired exposure rate. These rates are determined and verified using NBS certified R chambers and other instruments that have NBS traceability through the Sandia Measurements Standards Laboratory. The facility sources are calibrated at least once every two years, or they are calibrated as necessary if modifications or changes occur that might affect calibration values.

The SNL Radiation Standards Facility states the estimated error associated with the gamma calibration (C) to be 0.2 ± 3.4%.[3]

Errors Associated With Storage Shield Assumption

In determining the transit exposure for the WIPP TLDs, the assumption was that the exposure rates in both the Carlsbad and Albuquerque storage shields were equal; this equality would allow a comparison of the trip control and calibration dosimeters. The uncertainties associated with this comparison were treated as measurement errors and are included in the final WIPP results. However, if the original assumption was not valid, an additional bias (S_b) would be possible.

To test the validity of the assumption, a new assumption was made that the trip control dosimeters received no significant exposure during transit and that, therefore, the dosimeter response was really an estimate of the exposure in the Carlsbad shield. With this assumption, a direct comparison of the two storage shields can be made. The new assumption is reasonable since both the field and trip dosimeters were always handcarried between Albuquerque and Carlsbad, and the trip never took more than several hours.

To test the new assumption, 38 quarters of trip control and calibration control data were compared. Using the calibration control (Albuquerque shield) as reference, the average difference in the exposure rate was found to be −0.15 ± 0.14 μR/hr. This value would have been reflected as an underestimate in the trip control and would therefore result in an overestimate in the field result. Using the typical field exposure rate of 8.0 μR/hr, the percentage error due to the initial assumption (S_b) is 1.9 ± 1.8%.

Summary

The systematic errors having an impact on the accuracy of WIPP Environmental TLD Field Results are summarized in Table A1. The errors total 1.0 ± 7.2% and are normalized to the typical WIPP field exposure rate of 8.0 μR/hr. The total uncertainty is calculated by taking the square root of the sum of the squares of the individual uncertainties. The total bias is the algebraic sum of the individual biases.

While systematic errors are not usually reported with environmental dosimetry results, it is important to identify and examine those errors having a major impact on the program so that they can be controlled and possibly reduced.

Table A1. Systematic Errors That Have an Impact on the Accuracy of WIPP Environmental TLD Field Results

Parameter		*Error (%)* *Bias ± Uncertainty*
Calibration Timing Device		±0.07
Calibration Time Repeatability		±0.56
Field Cycle Length		±0.18
Shield Storage Length		±0.20
TLD Directional Dependence		−1.4 ±1.6
TLD Self-Irradiation		1.0 ±0.73
TLD Energy Response		−0.9 ±5.5
TLD Fade		0.2 ±1.1
Calibration Standard		0.2 ±3.7
Storage Shield Assumption		1.9 ±1.8
	Total Error	1.0 ±7.2

References

[A1]G. de Planque and T. F. Gessel, "Error Analysis of Environmental Radiation Measurements Made With Integrating Detectors," *Measurements for the Safe Use of Radiation,* S. P. Fivozinsky (Editor), U.S. Department of Commerce, NBS Special Publication 456, pp. 187—198, 1976.

[A2]H. L. Beck, "The Physics of Environmental Gamma Radiation Fields," *Proceedings of the Second International Symposium on Natural Radiation Environment,* AEC Symposium, Houston, TX, August 7—11, 1972.

[A3]B. L. O'Neal, "Gamma Source Calibration Procedures for the SNL Gamma Radiation Facility, Building 818," Internal Division 3313 Document, 1986.

APPENDIX B

ANALYSIS OF TLD MEASUREMENT ERRORS

Purpose

The purpose of this appendix is to describe the statistical procedures and computer program output used in the calibration and measurement error analysis of TLDs used to measure environmental background radiation. The statistical procedures were developed by D. D. Sheldon, 7223, and the computer program was written by L. F. West, 3313. An annotated sample computer output is attached.

TLDs were used to monitor environmental background radiation at field locations at the Waste Isolation Pilot Plant (WIPP). The field TLDs were used in sets of five and were replaced and measured on a quarterly basis. The TLDs do not measure radiation exposure directly; hence, a calibration is needed to relate their responses to actual radiation exposure. The calibration exposures applied are in milliRoentgens, mR, and the readouts are in units of charge. A set of calibration control units, which is kept in a lead shield except when it is being measured, is used to adjust dosimeter measurements for radiation background and instrument noise. The mean of the calibration control dosimeters is subtracted from the readings of calibration units subjected to specified amounts of radiation.

Prior to use in the field, TLDs are annealed as a single batch. A sample, n, is randomly selected from the annealed units and used for calibration midway through the exchange period, i.e., about 45 days after distributing field dosimeters. All TLDs, both field and calibration units, are read at the end of the 90-day period.

When field dosimeters are transported to the field sites, they are accompanied by a set of trip control dosimeters, whose purpose is to detect unexpected exposures during transportation. The mean of field or trip control dosimeter measurements is compared to the calibration control mean, to determine if a significant exposure has occurred during transit.

The mean of field or trip control dosimeter measurements is compared to the calibration control mean, to determine if a significant exposure has occurred during transit.

Data Quality Test

The measurements for calibration and field sets are tested for outliers, and outliers, if any, are removed from the data before proceeding with the analysis. The critical values used to identify outliers are a function of the number of observations in a set of dosimeters, say n, exposed to a known radiation level and the level of significance, a. The number of outliers removed, either high or low, is limited to 1/5 for each subgroup. If the proportion of outliers exceeds 1/5, the computer program is designed to alert the analyst. The procedure is as follows:

1. For each group of n dosimeters, calculate the residuals, i.e.,

$$r_i = \frac{Y_i - \bar{Y}}{s}, \qquad i = 1, 2, \ldots, n,$$

where Y_i is the reading on the ith dosimeter,

$$\bar{Y} = \frac{\sum_{i=1}^{n} Y_i}{n}$$ is the mean of the readings of the n dosimeters,

$$s = \sqrt{\frac{\sum_{i=1}^{n} Y_i^2 - \sum_{i=1}^{n} (Y_i)\ 2/n}{n - 1}}$$ is the standard deviation of the n dosimeters in a subgroup.

2. Arrange the r_i in ascending order, preserving the identification with the corresponding Y_i.

3. Reject the Y_i for which $|r_{(1)}^{i}| > r_{.025,n}$, where $r_{.025,n}$ is the critical value for $\alpha = .05$ and n.

Calibration

The calibration procedure consists of exposing at least three sets of dosimeters to as many known levels of radiation, one set per level, and measuring the responses of all the TLDs. The known inputs range from 10 to 80 mR. The responses are then adjusted by subtracting the mean of the calibration control dosimeters. All subsequent analyses are based on adjusted measurements. The set of calibration controls is also used to account for radiation background during storage and to account for instrument noise.

Once the outliers have been removed, the calibration control is subtracted from the exposed sets and a least-squares line is then fitted to the adjusted or net data, i.e.,

$$Y_{ij} = \alpha + \beta X_j + \epsilon_{ij} ,$$

where $i = 1, \ldots, n_j$,
$j = 1, \ldots, k$,
Y_{ij} is the (observed) reading for the ith TLD at the jth radition level,
X_j is the value of the jth known radition level,
ϵ_{ij} is the statistical error for the ith TLD at the jth radiation level,
n_j is the number of TLDs exposed to the jth radition level,
k is the number of known radiation levels,
and α and β are the intercept and slope of the calibration line, respectively.

Making multiple observations at a minimum of three radiation levels permits testing for lack-of-fit, i.e., for curvature. If curvature is detected, the computer program provides a diagnostic to alert the analyst. If curvature is not detected, i.e., a straight line adequately represents the data, a test is performed to determine whether the line goes through the origin, i.e., $\alpha = 0$. If $\alpha \neq 0$, a diagnostic alerts the analyst, otherwise, the slope through the origin is estimated, $\hat{\beta}_0$, and the corresponding estimated residual variance,

$\hat{\sigma}^2_\epsilon$, is obtained. The tests for curvature and zero intercept are both made at the 5% level of significance.

The fitted equation is now:

$$\hat{Y}_{ij} = \hat{\beta}_0 X_j + \epsilon_{ij} ,$$

$$i = 1, \ldots, n_j ,$$

$$j = 1, \ldots, k ,$$

where $\hat{Y}_{ij}$ is the estimated reading for the ith TLD and the jth radiation level

X_j is the jth radiation level

$\hat{\beta}_0$ is the least-squares estimate of the slope of the line through the origin,

and ϵ_{ij} is the random error, with estimated variance $\hat{\sigma}^2_\epsilon$

The equation used to estimate the exposure received by a TLD is then:

$$\hat{X}_i = \frac{\bar{Y}_i}{\hat{\beta}_0} , \; i = 1, \ldots, \ell,$$

where $\hat{X}_i$ is the estimated exposure for the ith site,

$\bar{Y}_i$ is the mean response of TLDs at a site,

$\hat{\beta}_0$ is the estimated slope,

and ℓ is the number of locations.

Field Exposures and Associated Errors

The radiation exposure values finally reported for the field sites are subject to a number of sources of variation in the measurement chain. The sources of error are: calibration line, storage, transit, inherent system background and the field dosimeters themselves. These sources of error are as follows:

Net Field Response = Field Response - Transit Response - Storage Response,

or $\bar{Y}_{NFRi} = \bar{Y}_{FRi} - \bar{Y}_{TR} - \bar{Y}_{SR} = \bar{Y}_{Fi} - \bar{Y}_{TC} + \left(1 - \frac{t_S}{t_T}\right)(\bar{Y}_{CC} - \bar{Y}_{RC})$ = mean , and

$$S^2_{NFR} = \frac{S^2_{Fi}}{n_{Fi}} + \frac{S^2_{TC}}{n_{TC}} + \left(1 - \frac{t_S}{t_T}\right)^2 \left(\frac{S^2_{CC}}{n_{CC}} + \frac{S^2_{RC}}{n_{RC}}\right) = \text{variance}$$

where t_S is the storage time for field TLDs, and

t_T is the time control TLDs are in shield.

The response components are:

1. Field Response = Field Readout - System Background

or $\bar{Y}_{FR} = \bar{Y}_{Fi} - \bar{Y}_{RC}$ = mean ,

$$S^2_{FR} = \frac{S^2_{Fi}}{n_{Fi}} + \frac{S^2_{RC}}{n_{RC}} = \text{variance}$$

and n_{Fi} and n_{RC} are the number of observations in the Field Readout and the reread of the Calibration Control averages.

2. Transit Response = Trip Control Response - Calibration Control Response

and $\bar{Y}_{TR} = \bar{Y}_{TC} - \bar{Y}_{CC}$ = mean ,

$$S^2_{TR} = \frac{S^2_{TC}}{n_{TC}} + \frac{S^2_{CC}}{n_{CC}} = \text{variance, and}$$

n_{TC} and n_{CC} are the number of observations for the Trip Control and Calibration Control samples, respectively.

3. Storage Response = t_S/t_T (Calibration Control Response - System Background) or $\bar{Y}_{SR} = \left(\frac{t_S}{t_T}\right)[\bar{Y}_{CC} - \bar{Y}_{RC}]$ = mean,

$$S_{SR}^2 = \left(\frac{t_S}{t_T}\right)^2 \left[\frac{S_{CC}^2}{n_{CC}} + \frac{S_{RC}^2}{n_{RC}}\right] = \text{variance},$$

where t_S = time that field dosimeters are stored in shield, and
t_T = time that calibration dosimeters are stored in shield .

The reported field dose for the ith site, and its 95% Confidence Limits, is:

$$\frac{\bar{Y}_{NFRi}}{\hat{\beta}_0} \pm \frac{t_{.025,f}}{\hat{\beta}_0} \left\{ S_{NFRi}^2 + \left(\frac{\bar{Y}_{NFRi}}{\hat{\beta}_0}\right)^2 \frac{ResMS}{\Sigma X^2} \right\}^{1/2} ,$$

where $t_{.025,f}$ = upper .025 percentile for student t with f degrees of freedom,
$\bar{Y}_{NFRi}$ = mean net Field Response for ith site,
$\hat{\beta}_0$ = estimated calibration slope,
S_{NFRi}^2 = variance of ith Net Field Response, at site i,
ResMS = residual mean square for calibration data,
ΣX^2 = sum of squares for calibration data.
and f = degrees of fredom calculated using Satterthwaite's formula.[(2)]

REFERENCES

(1) Grubbs, F. E., "Procedures for Detecting Outlying Observations in Samples," Technometrics (1969), v. 11, pp 1-21
(2) Satterthwaite, F. E. (1946), "An approximate distribution of estimates of variance components," Biom. Bull., 2, 110-114

ANNOTATION OF SAMPLE OUTPUT

1) $[\sum_j \sum_i X_{ij} Y_{ij} - (\sum_j \sum_i X_{ij})(\sum_j \sum_i Y_{ij})/n]^2 \div \left[\sum_j \sum_i X_{ij}^2 - \frac{(\sum_j \sum_i X_{ij})}{n}\right]^2$

= Model Sum of Squares

(2) $\sum_j \sum_i (Y_{ij} - \hat{Y}_{ij})^2$ = Residual Sum of Squares

(3) (2) - (4) = Lack-of-fit Sum of Squares

(4) $\sum_j (\sum_i Y_{ij}^2 - (\Sigma Y_{ij})^2/n_j)$ = Pure Error Sum of Squares

(5) $TSS = \sum_j \sum_i Y_{ij}^2 - (\sum_j \sum_i Y_{ij})^2/n$ = Total Sum of Squares

(6) $\hat{\alpha} = \bar{Y} - \hat{\beta}\bar{X}$ = Estimated Intercept

(7) $\hat{\beta} = [\sum_j \sum_i X_{ij} Y_{ij} - (\sum_j \sum_i X_{ij}) (\sum_j \sum_i Y_{ij})/n] \div \left[\sum_j \sum_i X_{ij}^2 - \frac{(\sum_j \sum_i X_{ij})^2}{n}\right]$

= Estimated Slope

8) $S_{\hat{\alpha}} = \left[\frac{\sum_j \sum_i X_{ij}^2 \quad s_\epsilon^2}{n(\sum_j \sum_i X_{ij}^2 - \frac{(\sum_j \sum_i X_{ij})^2}{n})}\right]^{1/2}$ = standard error of estimated intercept

9) $S_{\hat{\beta}} = \left[\frac{s_\epsilon^2}{\sum_j \sum_i X_{ij}^2 - \frac{(\sum_j \sum_i X_{ij})^2}{n}}\right]^{1/2}$ = standard error of estimated slope

10) $[\sum_j \sum_i X_{ij} Y_{ij}]^2 \div \sum_j \sum_i X_{ij}^2$ = Regression Sum of Squares with no intercept term

11) (12) - (10) = Residual Sum of Squares

12) $\sum_j \sum_i Y_{ij}^2$ = Total Sum of Squares

13) Mean Squares (MS) = (Sum of Squares) ÷ (Corresponding Degrees of Freedom)

14) Ratio of Model MS to Residual MS to test significance of regression line with intercept term

15) Ratio of Lack-of-fit MS to Pure Error MS to test for curvature

16) $t = \hat{\alpha}/S_{\hat{\alpha}}$ to test $\hat{\alpha} \stackrel{?}{=} 0$

17) $t = \hat{\beta}/S_{\hat{\beta}}$ to test $\hat{\beta} \stackrel{?}{=} 0$

18) Ratio of Model MS to Residual MS to test significance of calibration line, with no intercept term

19) $\hat{\beta}_0 = \sum_j \sum_i X_{ij} Y_{ij} / \sum_j \sum_i X_{ij}^2$ = estimate of slope thru the origin

20) $S^2_{\hat{\beta}_0} = \left[\dfrac{\text{Res Mean Squares}}{\sum_j \sum_i X_{ij}^2}\right]$ = variance of $\hat{\beta}_0$

21) $S_{\hat{\beta}_0} = \sqrt{(20)}$ = standard error of $\hat{\beta}_0$

22) $(S_{\hat{\beta}_0} / \hat{\beta}_0) \times 100$ = Coefficient of Variation

23) Sum of Squares (X) = ΣX_i^2

24) $$\text{d.f.} = \frac{\left\{\dfrac{S^2_{Fi}}{n_{Fi}} + \dfrac{S^2_{TC}}{n_{TC}} + \left[1 - \dfrac{t_S}{t_T}\right]^2 \left[\dfrac{S^2_{cc}}{n_{cc}} + \dfrac{S^2_{RC}}{n_{RC}}\right] + (\hat{X}_i)^2 \dfrac{\text{Res MS}}{\Sigma X_j^2}\right\}^2}{\dfrac{\left(\dfrac{S^2_{Fi}}{n_{Fi}}\right)^2}{n_{Fi}} + \dfrac{\left(\dfrac{S^2_{TC}}{n_{TC}}\right)^2}{n_{TC}} + \left[1 - \dfrac{t_S}{t_T}\right]^4 \left[\dfrac{\left(\dfrac{S^2_{cc}}{n_{cc}}\right)^2}{n_{cc}} + \dfrac{\left(\dfrac{S^2_{RC}}{n_{RC}}\right)^2}{n_{RC}}\right] + \left[(\hat{X}_i)^2 \dfrac{\text{Res MS}}{\Sigma X_i^2}\right]^2}$$

25) $\hat{X}_i = \bar{Y}_i / \hat{\beta}_0$, estimated exposure for ith location

26) $$t_{.025,df}(S_{\hat{X}}) = t_{.025,df}\left\{\frac{S^2_{Fi}}{n_{Fi}} + \frac{S^2_{TC}}{n_{TC}} + \left[1 - \frac{t_S}{t_T}\right]^2 \left[\frac{S^2_{cc}}{n_{cc}} + \frac{S^2_{RC}}{n_{RC}}\right] + (\hat{X}_i)^2 \frac{\text{Res MS}}{\Sigma X_j^2}\right\}^{1/2}$$

SAMPLE OUTPUT

SANDIA ENVIRONMENTAL TLD MONITORING PROGRAM

CALIBRATION DATA

PERIOD:	3RD QUARTER 1983
DATE OF CALIBRATION:	11/25/86

CALIBRATION SCHEDULE

DATE TLD'S ANNEALED:	7/26/83
DATE TLD'S EXPOSED:	11/ 1/83
DATE TLD'S READ:	11/19/83

READOUT SYSTEM PARAMETERS

UNIT:	Harshaw 2000-1
GAIN:	950 nC
NOMINAL HEAT RATE:	10 deg C/sec
HEAT TIME:	25 sec
READ LIMITS:	175-250 deg C

ORIGINAL CALIBRATION DATA

	CONTROL
1	0.587
2	0.529
3	0.604
4	0.691
5	0.702
6	0.648
7	0.673
8	0.632
9	0.698
10	0.724
N=	10
AVE	0.649
S=	0.061
CV=	9.436%

$$\bar{Y}_{cc} = \sum_{i=1}^{n} Y_i/n$$

$$S_{cc} = \left[\frac{\sum_{i=1}^{n} Y_i^2 - \frac{\left(\sum_{i=1}^{n} Y_i\right)^2}{n}}{n - 1} \right]^{1/2}$$

ORIGINAL CALIBRATION DATA

	10 mR	20 mR	30 mR	50 mR	80 mR
1	1.275	1.882	2.353	3.665	4.128
2	1.390	2.168	2.970	3.140	5.607
3	1.411	2.020	2.727	3.498	5.639
4	1.330	2.205	2.561	4.199	5.960
5	1.381	2.133	2.602	4.330	6.242
6	1.277	2.031	2.643	4.009	5.391
7	1.441	2.031	3.034	4.456	5.747
8	1.441	1.990	3.126	4.144	6.400
9	1.567	2.009	2.615	4.409	6.306
10	1.155	2.043	2.331	4.354	6.217
N=	10	10	10	10	10
AVE	1.367	2.051	2.696	4.020	5.764
S=	0.114	0.094	0.271	0.443	0.669
CV=	8.324%	4.596%	10.063%	11.029%	11.605%

CALIBRATION DATA RESET FOR OUTLIERS

	CONTROL
1	0.587
2	0.529
3	0.604
4	0.691
5	0.702
6	0.648
7	0.673
8	0.632
9	0.698
10	0.724
N=	10
AVE	0.649
S=	0.061
CV=	9.436%

	10 mR	20 mR	30 mR	50 mR	80 mR
1	1.275	1.882	2.353	3.665	6.217
2	1.390	2.168	2.970	3.140	5.607
3	1.411	2.020	2.727	3.498	5.639
4	1.330	2.205	2.561	4.199	5.960
5	1.381	2.133	2.602	4.330	6.242
6	1.277	2.031	2.643	4.009	5.391
7	1.441	2.031	3.034	4.456	5.747
8	1.441	1.990	3.126	4.144	6.400
9	1.567	2.009	2.615	4.409	6.306
10	1.155	2.043	2.331	4.354	0.000
N=	10	10	10	10	9
AVE	1.367	2.051	2.696	4.020	5.945
S=	0.114	0.094	0.271	0.443	0.363
CV=	8.324%	4.596%	10.063%	11.029%	6.104%

ONE OUTLIER DELETED

ANALYSIS OF VARIANCE TABLE
DATA REPRESENTED BY A STRAIGHT LINE

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
MODEL	1	123.821100 (1)	123.8211	1575.59 (14)
RESIDUAL	47	3.693601 (2)	0.0786 (13)	
LACK OF FIT	3	0.011390 (3)	0.0038	0.05 (15)
PURE ERROR	44	3.682211 (4)	0.0837	
TOTAL	48	127.514500 (5)		

PARAMETER ESTIMATES

PARAMETER	ESTIMATE	STANDARD ERROR	T
INTERCEPT	0.0844851 (6)	0.0730916 (8)	1.1559 (16)
SLOPE	0.0653429 (7)	0.0016462 (9)	39.6937 (17)

ANALYSIS OF VARIANCE TABLE
DATA REPRESENTED BY A STRAIGHT LINE THROUGH THE ORIGIN

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUMS OF SQUARES	MEAN SQUARES	F RATIO
SLOPE	1	432.791600 (10)	432.7916 (13)	5469.05 (18)
RESIDUAL	48	3.798462 (11)	0.0791	
TOTAL	49	436.590100 (12)		

CALIBRATION INFORMATION

SLOPE (B): 0.06688948 (19)

VARIANCE OF B: 0.00000271 (20)

STANDARD ERROR OF B: 0.00164618 (21)

COEFFICIENT OF VARIATION OF B: 2.46% (22)

CALIBRATION VALUES SAVED FOR CALCULATION OF FIELD DATA

DATE CALIBRATION VALUES WERE CALCULATED: 11/25/86

CONTROL AVERAGE: 0.649

NUMBER OF CHIPS IN THE CONTROL ARRAY: 10

CONTROL STANDARD DEVIATION: 0.06122

CONTROL VARIANCE: 0.00374821

SUM OF SQUARES (X): 96600 (23)

RESIDUAL MEAN SQUARE (Y): 0.079135

RESIDUAL DEGREES OF FREEDOM: 48

SLOPE OF LINE GOING THROUGH THE ORIGIN (B): 0.06688948 (19)

SANDIA ENVIRONMENTAL TLD MONITORING PROGRAM

FIELD DATA - WIPP

PERIOD: 3RD QUARTER 1983

FIELD SCHEDULE

DATE TLD'S ANNEALED:	7/26/83	
STORAGE DATES (PRE-ISSUE):	7/26/83 TO 7/28/83	2 DAYS
FIELD CYCLE DATES:	7/29/83 TO 11/10/83	104 DAYS
STORAGE DATES (POST-ISSUE):	11/11/83 TO 11/19/83	8 DAYS
DATE TLD'S READ:	11/19/83	
EXPOSURE CYCLE DATES:	7/26/83 TO 11/19/83	114 DAYS

READOUT SYSTEM PARAMETERS

UNIT:	Harshaw 2000-1
GAIN:	950 nC
NOMINAL HEAT RATE:	10 deg C/sec
HEAT TIME:	25 sec
READ LIMITS:	175-250 deg C

CALCULATION VALUES FROM CALIBRATION STEP

DATE CALIBRATION VALUES WERE CALCULATED: 11/25/86

CONTROL AVERAGE: 0.649

NUMBER OF CHIPS IN THE CONTROL ARRAY: 10

CONTROL STANDARD DEVIATION: 0.06122

CONTROL VARIANCE: 0.00375

SUM OF SQUARES (X): 96600 (23)

RESIDUAL MEAN SQUARE (Y): 0.07913

RESIDUAL DEGREES OF FREEDOM: 48

SLOPE OF LINE GOING THROUGH THE ORIGIN (B): 0.06689 (19)

ORIGINAL FIELD DATA

SYSTEM BACKGROUND

N=	40
AVE	0.038
S=	0.025
CV=	65.789%

TRIP CONTROL

1	0.597
2	0.515
3	0.585
4	0.567
5	0.540
6	0.582
7	0.610
8	0.613
9	0.615
10	0.582

N=	10
AVE	0.581
S=	0.033
CV=	5.604%

	MET STA	BADGER	ERDA 6	AEC 7	AEC 8
1	1.114	1.304	1.180	1.289	1.287
2	1.190	1.230	1.126	1.497	1.460
3	1.281	1.157	1.055	1.324	1.447
4	1.260	1.327	1.260	1.339	1.470
5	1.211	1.250	1.215	1.320	1.367
N=	5	5	5	5	5
AVE	1.211	1.254	1.167	1.354	1.406
S=	0.065	0.067	0.080	0.082	0.078
CV=	5.406%	5.326%	6.820%	6.064%	5.551%

	ERDA 9	WIPP II
1	1.234	1.183
2	1.153	1.210
3	1.281	1.179
4	1.221	1.171
5	1.272	1.245
N=	5	5
AVE	1.232	1.198
S=	0.051	0.030
CV=	4.132%	2.528%

FIELD DATA RESET FOR OUTLIERS

SYSTEM BACKGROUND

N=	40
AVE	0.038
S=	0.025
CV=	65.789%

TRIP CONTROL

1	0.597
2	0.515
3	0.585
4	0.567
5	0.540
6	0.582
7	0.610
8	0.613
9	0.615
10	0.582

N=	10
AVE	0.581
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CV=	5.604%

	MET STA	BADGER	ERDA 6	AEC 7	AEC 8
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2	1.190	1.230	1.126	1.320	1.460
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4	1.260	1.327	1.260	1.339	1.470
5	1.211	1.250	1.215	0.000	1.367
N=	5	5	5	4	5
AVE	1.211	1.254	1.167	1.318	1.406
S=	0.065	0.067	0.080	0.021	0.078
CV=	5.406%	5.326%	6.820%	1.593%	5.551%

ONE OUTLIER REMOVED

	ERDA 9	WIPP II
1	1.234	1.183
2	1.153	1.210
3	1.281	1.179
4	1.221	1.171
5	1.272	1.245
N=	5	5
AVE	1.232	1.198
S=	0.051	0.030
CV=	4.132%	2.528%

Transit Response

Temporary Transit Response = Trip Control - Calibration Control

Temporary Transit Response = 0.58060 - 0.64880 = -0.06820 +/- 0.02192

t(data) = 3.111 t(95%) = 2.101

Transit Response = 0.00000 +/- 0.02192

Storage Response = 0.05358 +/- 0.00173

Shield Exposure Rate = 3.338 +/- 0.253 uR/hr

DEGREES OF FREEDOM (DOF) TABLE

LOCATION	DOF INCLUDING CAL		DOF NOT INCLUDING CAL
MET STA	12		8
BADGER	12		8
ERDA 6	9		7
AEC 7	44	(24)	18
AEC 8	10		7
ERDA 9	18		11
WIPP II	36		18

SANDIA ENVIRONMENTAL TLD MONITORING PROGRAM

11-25-1986 INTERPERIOD EXPOSURE REPORT WIPP

PERIOD: 3RD QUARTER 1983
FIELD CYCLE DATES: 7/29/83 TO 11/10/83 104 DAYS

Estimate of error at the 95% confidence level includes the uncertainty of the calibration

LOCATION	EXPOSURE (mR)	EXPOSURE RATE (uR/hr)
MET STA	(25)16.7 +/- 1.3 (26)	6.7 +/- 0.5
BADGER	17.4 +/- 1.3	7.0 +/- 0.5
ERDA 6	16.1 +/- 1.5	6.4 +/- 0.6
AEC 7	18.3 +/- 0.9	7.3 +/- 0.4
AEC 8	19.7 +/- 1.5	7.9 +/- 0.6
ERDA 9	17.1 +/- 1.1	6.8 +/- 0.4
WIPP II	16.5 +/- 0.9	6.6 +/- 0.4

SANDIA ENVIRONMENTAL TLD MONITORING PROGRAM

11-25-1986 INTRAPERIOD EXPOSURE REPORT WIPP

PERIOD: 3RD QUARTER 1983
FIELD CYCLE DATES: 7/29/83 TO 11/10/83 104 DAYS

Estimate of error at the 95% confidence level does not include the uncertainty of the calibration

LOCATION	EXPOSURE (mR)	EXPOSURE RATE (uR/hr)
MET STA	16.7 +/- 1.2	6.7 +/- 0.5
BADGER	17.4 +/- 1.3	7.0 +/- 0.5
ERDA 6	16.1 +/- 1.5	6.4 +/- 0.6
AEC 7	18.3 +/- 0.7	7.3 +/- 0.3
AEC 8	19.7 +/- 1.4	7.9 +/- 0.6
ERDA 9	17.1 +/- 1.0	6.8 +/- 0.4
WIPP II	16.5 +/- 0.8	6.6 +/- 0.3

SANDIA ENVIRONMENTAL TLD MONITORING PROGRAM

11-25-1986 INTERPERIOD EXPOSURE REPORT WIPP

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SANDIA ENVIRONMENTAL TLD MONITORING PROGRAM

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