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FACTORS AFFECTING THE USE OF CaF_2:Mn THERMOLUMINESCENT DOSIMETERS FOR LOW-LEVEL ENVIRONMENTAL RADIATION MONITORING

Environmental Monitoring and Support Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio

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FACTORS AFFECTING THE USE OF CaF_2:Mn THERMOLUMINESCENT DOSIMETERS FOR LOW-LEVEL ENVIRONMENTAL RADIATION MONITORING

by

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FOREWORD

Environmental measurements are required to determine the quality of ambient waters and the character of waste effluents. The Environmental Monitoring and Support Laboratory - Cincinnati conducts research to:

- Develop and evaluate techniques to measure the presence and concentration of physical, chemical, and radiological pollutants in water, wastewater, bottom sediments, and solid waste.
- Investigate methods for the concentration, recovery, and identification of viruses, bacteria and other microbiological organisms in water.
- Conduct studies to determine the responses of aquatic organisms to water quality.
- Conduct an agency-wide quality assurance program to assure standardization and quality control of systems for monitoring water and wastewater.

With the increased use of nuclear power for generation of electricity, environmental radioactivity monitoring programs must be improved and tested to measure accurately the radiation exposure to affected individuals and population groups. The Environmental Protection Agency is engaged in studies to develop methodology and to provide information for evaluating such monitoring programs. One element of this research is the evaluation of the use of thermoluminescent dosimetry for the measurement of external radiation dose in the environment of these power stations.

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ABSTRACT

An investigation was made of factors affecting the use of commercially-produced CaF_2:Mn thermoluminescent dosimeters for low level environmental radiation monitoring. Calibration factors and self-dosing rates were quantified for 150 thermoluminescent dosimeters. Laboratory studies were made of precision, linear response to dose rate, effects of light, and time-dependent fading. A standard laboratory procedure was devised and a computer program was written to calculate, analyze, and store the large amounts of data that were accumulated. Extensive environmental measurements were subsequently carried out at the Vermont Yankee Nuclear Power Station. The results of this investigation indicate that selected dosimeters, when properly calibrated and corrected for self-irradiation, can be used for accurate and reliable monitoring of low-level environmental radiation.

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SECTION I
INTRODUCTION

Accurate determination of radiation from nuclear power stations, of the same magnitude as variations in the natural background radiation in the vicinity, requires sensitive dosimeters capable of accurate and precise measurements. To meet these requirements, techniques were developed to calibrate and evaluate commercially available, glass-encapsulated CaF_2:Mn thermoluminescent dosimeters for gamma-ray measurements. These dosimeters have been studied previously and have been found well suited for low-level measurements(1-3). This report discusses the feasibility and the practicability of this dosimeter as a reliable gamma radiation monitor.

SECTION II
CONCLUSION

The present investigation has shown that glass-encapsulated CaF_2:Mn dosimeters are capable of accurate and reliable measurements of low-level environmental radiation. These dosimeters, when properly calibrated and corrected for internal background, can play a vital role in the environmental monitoring of operating nuclear power facilities, and can measure environmental radiation exposures attributable to a facility at levels as low as 8 mR/yr.

SECTION III
PHYSICAL CHARACTERISTICS OF THE TLD SYSTEM

The thermoluminescent dosimeter (TLD) system studied consists of CaF_2:Mn thermoluminescent dosimeters and a low-level thermoluminescent dosimeter reader. The system was originally manufactured by EG&G, Inc. but, with slight modification, is now manufactured by the Victoreen Instrument Division. The dosimeter, (Victoreen Model 2600-46), shown in Figure 1, consists of two manganese-activated thermoluminescent CaF_2:Mn chips, firmly attached to a flat heating element. The thermoluminescent material and heating element are contained within a carbon dioxide-filled glass bulb, 1.1 cm in diameter and 3.1 cm long. The bulb is housed in an aluminum-lead-tin shield to reduce the dosimeter's non-linear response to low-energy gamma rays. A curve of response versus energy for this detector has been provided by the manufacturer and is reproduced in Figure 2(4). The curve indicates that the response per roentgen shows only small variation with photon energy above approximately 65 keV.

The semi-automatic reader unit (EG&G Model TL 3A) furnishes data in the form of a glow curve which are permanently recorded on a 13 cm paper strip chart. The reader is calibrated with a phosphorescent reference light source with a physical configuration similar to that of the dosimeter. The reader is equipped with a photomultiplier tube and a voltage discriminator which allows the suppression of signals which are due to electrical background noise. A reading head positions the dosimeter in a light-tight chamber and passes a constant current of 6.5 amps through the heating element. The photomultiplier tube then converts the emitted thermoluminescence into an electrical current which is proportional to the magnitude of the gamma-ray exposure. The plot of thermoluminescent light output as a function of time is known as a glow curve. Examples of a calibration glow curve and a typical readout glow curve are reproduced in Figure 3. The magnitude of the exposure is determined by measuring the height of the peak (see Figure 3b). To interpret the glow curve for the dosimeter in Figure 3, it is necessary to ignore the horizontal "pip" extending to the extreme right of the chart paper which indicates that the reading exceeded full-scale deflection and the range switch automatically stepped up to the next scale. In the case shown in Figure 3b, the range changed once from the 0-5 unit scale to the 0-50 unit scale. The peak of the main glow curve then fell at 47.2 units.

Available for this investigation were 100 dosimeters from one manufacturer (EG&G) designated as Group A, and fifty dosimeters from a second manufacturer (Victoreen Instruments Division) designated as Group B (a redesigned and improved version of the EG&G dosimeter). The basic difference between the two groups of dosimeters is that the Group B dosimeters are designed with larger lead wires (0.98 mm diameter compared with 0.84 mm for the Group A dosimeters) and the glass of the bulb material for the Group B dosimeters contains a smaller amount of radioactive potassium-40 impurities.

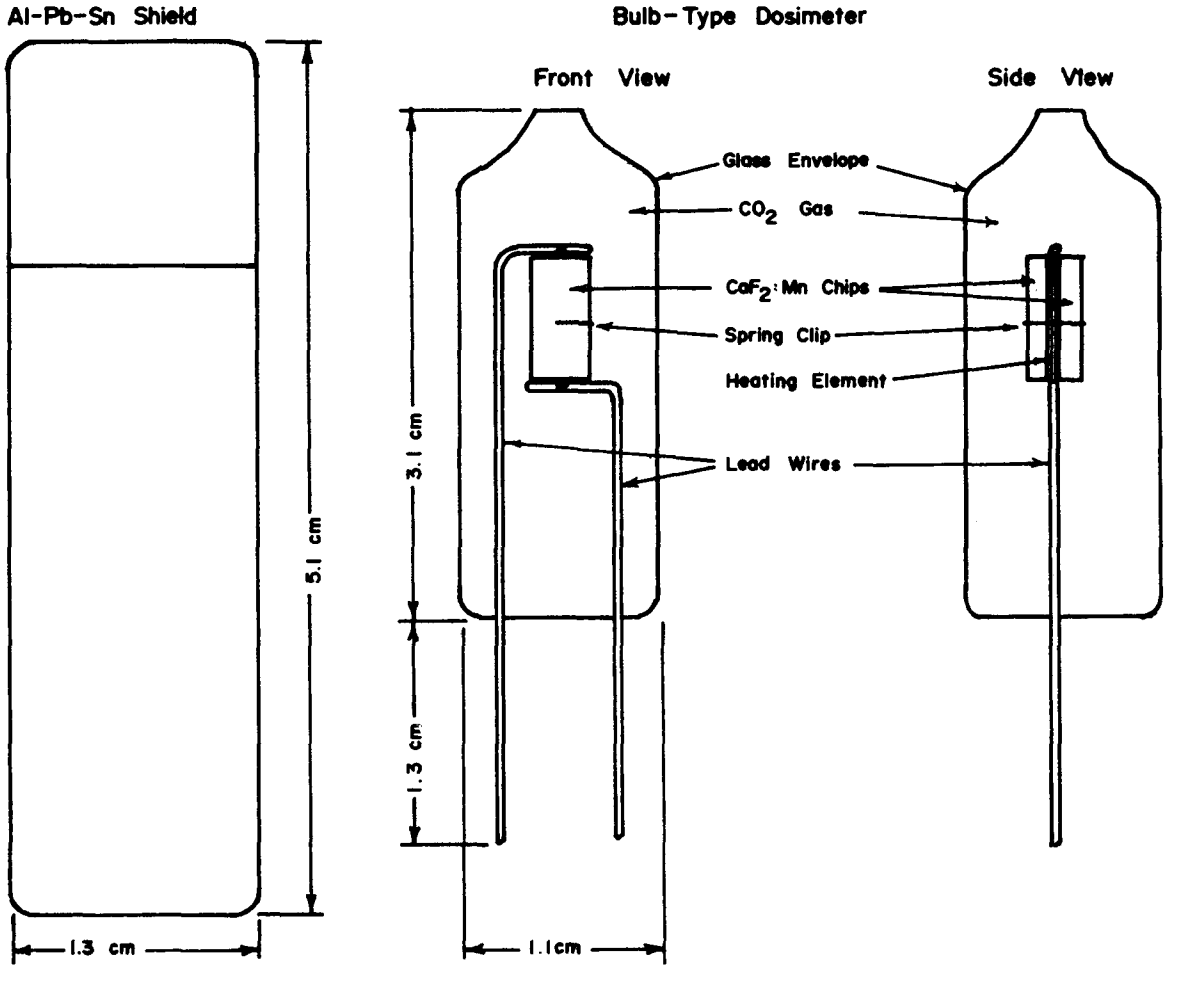


Figure 1. Bulb-Type Dosimeter and Shield

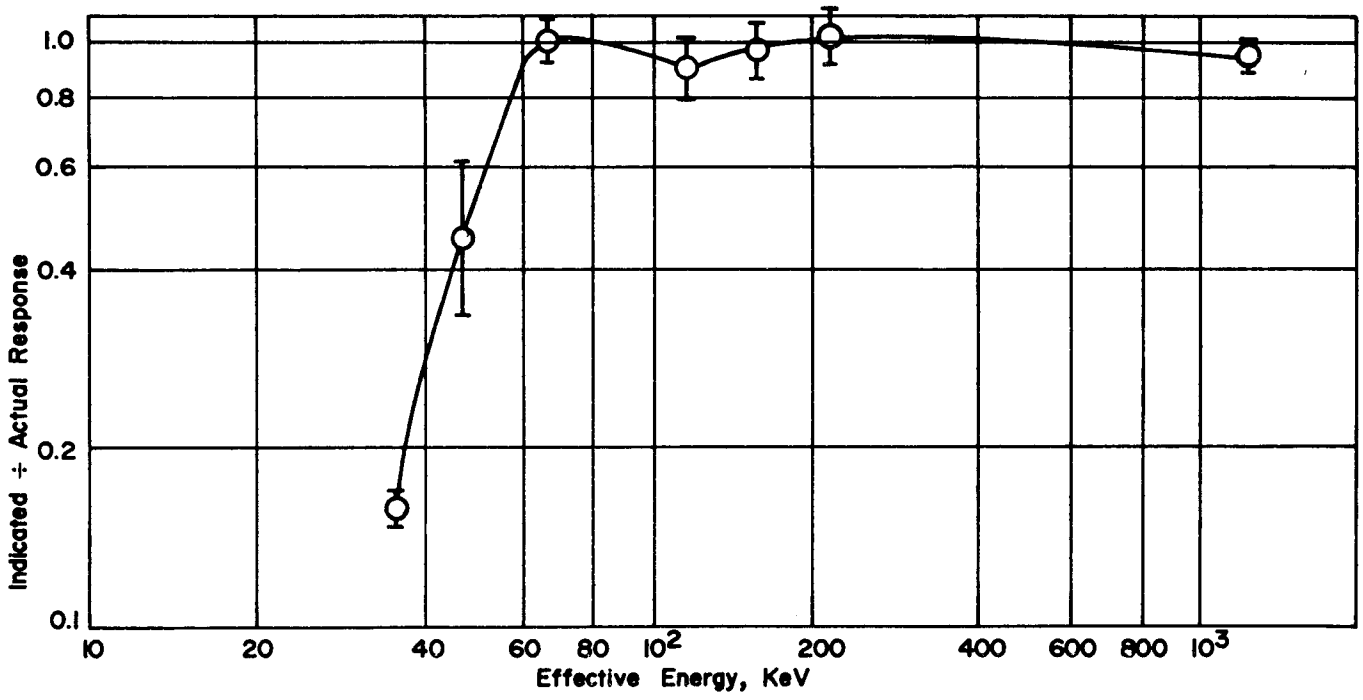
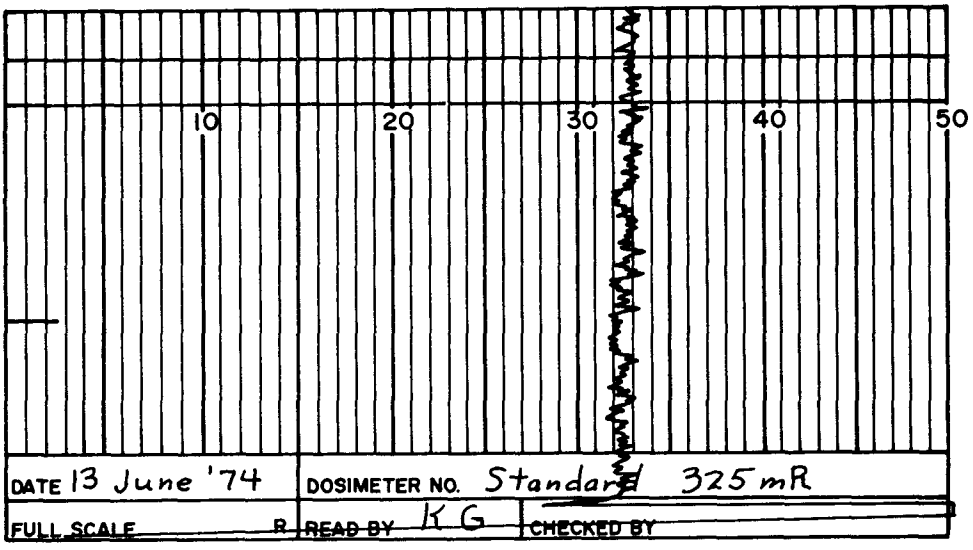
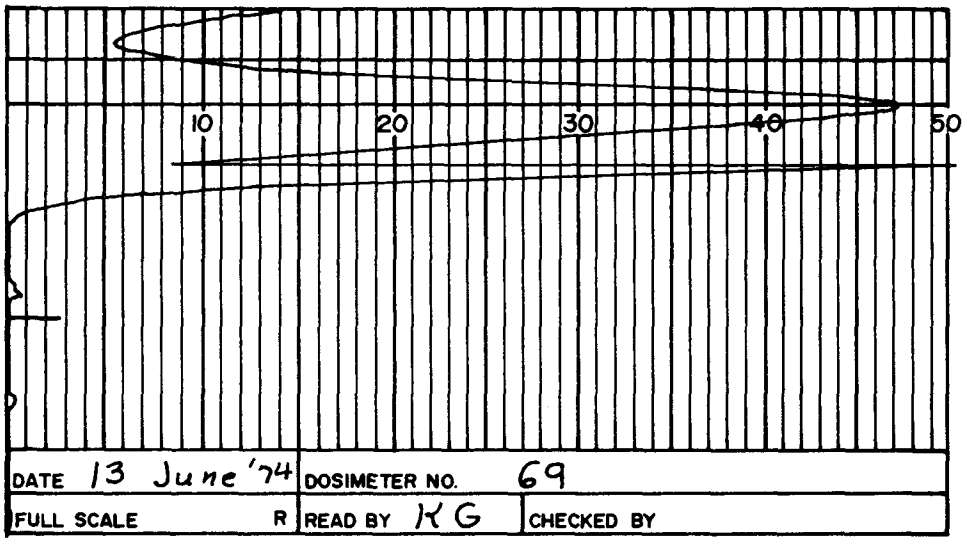


Figure 2 Response vs. Energy Curve for Shielded Dosimeter



a. 325 mR Calibration Standard



b. 47.2 mR – One Scale Change

Figure 3 Strip Chart Recorder Output

SECTION IV
METHODS AND PROCEDURES

CALIBRATION PROCEDURES

The glow curve peak height obtained in reading out an irradiated detector is directly proportional to the amount of radiation exposure i.e., to the radiation dose received by the dosimeter material. However, the constant of proportionality varies from dosimeter to dosimeter. Consequently, calibration factors were obtained to convert peak heights, in arbitrary units, to exposure in milliroentgen (mR). The calibration factors for all dosimeters studied were obtained by exposing each dosimeter a minimum of seven times to a known quantity of radiation and dividing the dose by the reading produced. A 2 mCi ^{226}Ra source, calibrated by the National Research Laboratories of Canada, was used to expose the dosimeters on a specially constructed calibration facility. The facility was designed to provide reproducible positioning of the dosimeters and to minimize errors introduced by scatter. It has a plexiglass source holder permanently fixed at its geometric center and dosimeter holders fixed at equal radial distances (50.0 cm) along the periphery. Since the source strength and the distance between the source and the dosimeters are known, the total exposure to the dosimeters for a given calibration experiment can be determined by measuring the time during which the dosimeters are exposed to the source. Throughout this study, the dosimeters were given exposures ranging from 5 mR to 12 mR and read 24 hours later.

The mean calibration factors for the dosimeters from Group A varied from 0.20 to 0.27 mR/reader unit. The average standard deviation of the mean calibration factor for an individual dosimeter from Group A was 1.8 percent. The standard deviation of the entire population was 4.4 percent. The mean calibration factors for Group B varied from 0.29 to 0.31 mR/reader unit and the average of the individual standard deviations was 1.4 percent. The standard deviation of the population for Group B was 2.0 percent.

The difference in sensitivity between Group A and Group B is attributed to the previously mentioned design differences between the two groups of dosimeters. For the purpose of this study, unique calibration factors were determined and used for each dosimeter. Using these individual calibration factors, the error in the precision and reproducibility of this dosimeter-reader system is not greater than 1.8 percent. However, if less precision is required in a given monitoring situation, use of an average calibration factor for the dosimeters from Group B would lead to an error not greater than 3.3 percent.

The variation in response of any individual dosimeter between successive readings can be attributed to several factors. These include uncertainty in reader calibration, the error in peak height determination, and the error in determining the actual exposure to the dosimeters.

Calibration of the reader involves adjustment of the zero position of the strip chart recorder, the voltage of the photomultiplier tube, and the

heater current. The adjustment of the strip chart recorder zero setting is checked each time a group of dosimeters is to be read out. The adjustment is necessary to nullify the variations in the photomultiplier tube dark current. Dark current, the photomultiplier tube anode current measured with no light source, has been observed to fluctuate over a small range daily. The adjustment can be made by inserting the empty read head into the reader and manipulating the zero control until a zero reading is obtained on the chart recorder. The zero can easily be adjusted to within $\pm$ 0.1 reader units; hence, the error attributable to the adjustment of the zero is about 0.3 percent for a 9 mR exposure, and 0.9 percent for a 3 mR exposure.

The high voltage on the photomultiplier tube is adjusted by inserting a reference light source and adjusting the fine gain control until the pen indicates the value assigned to the reference light. The potential error introduced by the reproducibility of this adjustment is less than 0.6 percent if the same reference light source is used for every calibration.

The adjustment of the heater current to 6.5 amps is accomplished with the aid of a built-in ammeter. This adjustment is very important because fluctuations in the heating current, and hence the heating rate, can have pronounced effects on the glow curve (5). The area under the glow curve is not affected, but the shape of the curve is altered and the height of the peak is shifted by a change in the heating rate. The current, when adjusted properly, has not been observed to fluctuate with time; assuming the setting is not changed manually, the source of error from this adjustment can be considered minor (less than 0.1 percent of the total error).

The peak height can be read to within $\pm$ 0.2 reader units. The error in this determination can amount to 0.6 percent for a 9 mR exposure, and 1.8 percent at 3 mR.

The uncertainty in the radium source strength for the source used to expose the dosimeters is 2.2 percent. The error in the measurement of the distance between the source and the detectors is about 0.2 percent at 50 cm. The uncertainty in the positioning of the detector inside its shield contributes another 0.2 percent.

The dose which is due to scattering from the floor and ceiling of the calibration facility room, as well as that which is due to air scatter, is quantified and subtracted from the total dose. This is accomplished by annealing three to five reference dosimeters and placing them behind a lead brick so they are "shadowed" from the radium source. These reference dosimeters will only measure the component of the total dose which is due to scatter and the natural background. Since this component is being subtracted out, the uncertainty in the calibration factors which may be due to scatter can be neglected.

Other possible sources of error include the dose due to the ambient background which the dosimeters receive between the time they are annealed and the time they are read out. This error was minimized during this investigation by storing the dosimeters in a large shield with 15-cm-thick steel walls after exposure to the radium source until the time they are read. The extra dose which is accumulated in this way is in the order of 0.069 $\pm$ 0.009 mR in one day. Thus, the error introduced here for a total exposure of 9 mR is about 0.1 percent, and for a 3 mR exposure it is 0.3 percent. The error which is attributable to the fading of the dose between the time of exposure and the time of readout (cf. page 27) is approximately 0.03 percent.

All of these contributions to the total error have been tabulated in Table 1 for a 9 mR exposure to the dosimeters in Group A. Each contribution has been listed in the column on the right. A typical calibration factor, using the above data was found to be 0.240 ± 0.0056. The calculations, including the determination of the error term by propagation of errors, are shown in detail in Appendix A.

Table 1. Contributions to Error in Calibration Factor Determination for 9 mR Exposure to Dosimeters in Group A

Component	Value
Peak Height	37.5 ± 0.2 units
Zero Adjustment	± 0.1 units
High Voltage	± 0.23 units
Time of Exposure	86.25 ± 0.08 min
Ra Source, Measured at 50 cm	6.190 ± 0.134 mR/hr
Distance, Source to Detector	50.0 ± 0.2 cm
Dose Due to Ambient Background	0.069 ± 0.006 mR
Fading of Dose	negligible
Internal Background	0.046 ± 0.004 mR

INTERNAL BACKGROUND

The internal background (self irradiation) of the dosimeters is due to radioactivity in the glass and metal components used to construct the dosimeter. The internal backgrounds for all the dosimeters investigated were determined by annealing and placing them in a storage container with 15-cm-thick steel walls for a period of one to two weeks. The natural background within the container was measured with a tissue-equivalent ionization chamber and confirmed with a high-pressure ionization chamber to be 2.00 ± 0.10 micro-roentgen (μR) per hour. The internal background for the dosimeters was then obtained by subtracting the container background dose from the total dose accumulated by each dosimeter.

Values obtained from this procedure ranged from 1.7 to 2.5 μR/hr in Group A. The standard deviations for individual dosimeters in this group varied from 0.06 to 0.27 μR/hr. The average internal background for the group was 2.37 μR/hr and the average standard deviation was 0.13 μR/hr.

In Group B the internal backgrounds ranged from 1.5 to 1.8 μR/hr. The individual standard deviations in this group varied from 0.04 to 0.15

μR/hr. The average internal background for Group B was 1.63 μR/hr and the average standard deviation was 0.09 μR/hr.

From the large spread in the values from Group A, it is apparent that the internal background should be determined separately for each dosimeter. On the other hand, all the dosimeters in Group B could be assigned the average value for the entire group and the error introduced would be less than 10 percent.

The various contributions to the theoretical error in the internal background for a dosimeter from Group A are shown in Table 2. In arriving at the values given in the table, it was assumed that the group of dosimeters was left in the steel shield for a period of 168 hours.

Table 2. Contributions to Error in Internal Background Determination for Group A Dosimeters Left in Shield One Week

Component	Value
Calibration Factor	240 ± 5.6
Time	168 ± 0.17 hr
Reading	2.80 ± 0.02 units
Zero Adjustment	± 0.01 units
High Voltage	± 0.023 units
Ambient Background Outside Shield	14 ± 7.3 μR
Background in Shield	2.00 ± 0.10 μR/hr

The major source of error is the natural background in the shield. Another large source of error is the uncertainty in the calibration factor. The error due to the ambient background exposure which the dosimeters accumulate in transit from the time they are annealed to the time they are placed in the steel storage shield, and from the time they are removed from the storage shield until the time they are read out is small. The resultant theoretical uncertainty in an internal background for a dosimeter from Group A is 7.8 percent as computed in Appendix B by propagation of errors.

THEORETICAL ERROR FOR ENVIRONMENTAL MONITORING

The theoretical error in measuring low-level environmental radiation with the type of dosimeter used here will be a combination of the error in the calibration factors and internal backgrounds, as well as the error in

the determination of the time the dosimeters are actually in the environment and the error in the readout produced.

The experimental error in the calibration factor for both groups of dosimeters has been stated to be 2.3 percent. The experimental error in the internal background is 7.8 percent. The error in the determination of the peak height is about 1.3 percent for a 6 mR exposure, which is a typical environmental exposure over a monitoring period of one month. The time during which the dosimeters are in the environment can be determined to within 0.1 percent.

Using propagation of errors, the theoretical error in the net dose rate (environmental dose rate minus internal background) for a 6 mR total exposure accumulated over a 700 hour monitoring period by the dosimeters in Group A is calculated in Appendix C. The value of 4.1 percent represents the precision or reproducibility of this dosimeter-reader system at a typical environmental radiation level.

PRECISION AND ACCURACY OF DOSIMETERS AS A GROUP

Ten dosimeters whose calibration factors and internal backgrounds were well known were chosen from Group A and a simulated environmental measurement was made to quantify the precision attainable with dosimeters used in a group. The selected dosimeters were annealed and placed in a laboratory for ten one-month periods. The previously-discussed corrections were applied to all readings and the results of the ten measurements are listed in Table 3. The mean values listed in column 1 were obtained by averaging the net dose rates over the ten dosimeters. The average standard deviation from the mean (column 2) was 1.1 percent. This is considered well within the range of the desired precision for environmental measurements.

Table 3. Trial Exposures of 10 Dosimeters

Date	Mean Dose Rate (μR/hr)	Standard Deviation of Mean (%)	Maximum Deviation from Mean (%)
November 1973	9.02	1.4	6.4
December 1973	8.84	1.1	5.9
January 1974	8.83	0.9	5.8
February 1974	8.71	0.9	4.8
March 1974	8.00	1.1	5.9
April 1974	8.78	1.0	5.9
May 1974	8.89	1.1	5.4
June 1974	8.48	1.1	5.9
July 1974	8.72	1.1	4.6
August 1974	8.95	1.4	5.2

A similar measurement was subsequently made to determine the accuracy of the mean value of a group of dosimeters. For this measurement, twenty dosimeters were selected from Group A and were placed in the laboratory

with a pressurized ionization chamber (PIC) and with a NaI(Tl) survey meter. After an exposure time of 68 hours, the dosimeters were read out and the readings obtained were converted to dose rates. Results are shown in Table 4. The 1.4 percent higher value found from the survey meter readings is attributed to the fact that it was used to obtain instantaneous readings, whereas the dosimeters and the PIC were measuring continuously over the 68-hour period. The performance is excellent when it is observed that the dosimeters were exposed to a total environmental dose of 0.65 mR.

Table 4. Simulated Environmental Exposure of 20 Dosimeters from Group A

Measurement Technique	Mean Dose Rate (uR/hr)	Standard Deviation (%)
TLD (20 Dosimeters)	9.63	1.8
Pressurized Ionization Chamber	9.61	2.0
NaI(Tl) Survey Meter	9.70	2.1

COMPUTER PROGRAM

Since calibration factors and internal backgrounds were measured separately for each of the 150 dosimeters, large amounts of data were accumulated. To simplify the calculation, analysis, and storage of these data, a FORTRAN computer program listed in Appendix D, was written. The program is designed to store the calibration factors and the internal backgrounds for each dosimeter. It calculates the mean calibration factor and internal background with the standard deviation for each dosimeter. It then scans the data, eliminates readings which deviate by more than 3 sigma from the mean, and calculates a new mean and a new standard deviation. Finally, it averages the means of all the dosimeters and calculates the standard deviation of the population and the standard deviation of the mean for the entire batch of dosimeters. Examples of the print-outs produced by the program are reproduced in Tables 5 and 6.

The data stored in the program can be updated at any time. Any of the existing data can be altered or deleted (note options 1 and 3 on the output sheets in Tables 5 and 6). Whenever any of the data change, all means and standard deviations are automatically re-calculated. Also, when new data cause refinement of a dosimeter's calibration factor, the program recalculates the internal backgrounds using the new calibration factor.

The program also has the capability of performing dose rate calculations. The readings for a batch of dosimeters, as well as the number of hours the dosimeters were being exposed, are entered as input. The program then takes the most up-to-date calibration factor and internal background for each dosimeter in the group and calculates the total dose, the dose rate, and the net dose rate for each dosimeter. The results are printed out in tabular form, as well as the mean and standard deviation of

TABLE 5

COMPUTER PRINTOUT OF INDIVIDUAL TLD DATA

```
 what do you want to do?
code. . . 0=obtain a print out of calibration factor data
          1=add to or change calibration data
          2=obtain a print out of internal background data
          3=add to or change internal background data
          4=obtain a list of tld's,calibration factors,and internal bkgs.
          5=obtain statistical information on all tlds
          6=perform dose rate calculations
V4

you will get a print out for tlds n thru m
enter n and m
V401,425
```

tld	cal. fact.	sigma	number of readings	int. bkg	sigma	number of readings
401	0.318	0.003	7	1.87	0.122	7
402	0.337	0.005	7	1.93	0.119	9
403	0.326	0.005	8	1.98	0.154	8
404	0.328	0.005	8	1.93	0.114	8
405	0.322	0.005	7	1.85	0.102	9
406	0.325	0.003	7	1.99	0.146	8
407	0.327	0.005	7	1.97	0.131	9
408	0.331	0.007	7	1.87	0.135	9
409	0.327	0.006	7	1.96	0.109	8
410	0.334	0.007	8	1.96	0.144	9
411	0.313	0.003	7	1.92	0.113	8
412	0.313	0.005	7	1.87	0.157	7
413	0.319	0.003	7	1.92	0.132	8
414	0.325	0.005	7	1.90	0.117	8
415	0.320	0.004	7	1.98	0.074	7
416	0.307	0.005	8	1.86	0.060	8
417	0.328	0.005	8	1.85	0.080	8
418	0.321	0.005	7	1.89	0.082	9
419	0.328	0.004	7	1.99	0.084	8
420	0.321	0.006	7	1.86	0.121	9
421	0.322	0.006	7	2.11	0.112	6
422	0.316	0.006	8	2.02	0.110	8
423	0.319	0.004	7	2.19	0.095	9
424	0.327	0.005	7	1.93	0.133	7
425	0.328	0.005	7	1.92	0.104	9

```
stop
time 3 secs.
```

TABLE 6

COMPUTER PRINTOUT OF AVERAGE TLD DATA

```
 what do you want to do?
code. . . 0=obtain a print out of calibration factor data
          1=add to or change calibration data
          2=obtain a print out of internal background data
          3=add to or change internal background data
          4=obtain a list of tld's,calibration factors,and internal bkgs.
          5=obtain statistical information on all tlds
          6=perform dose rate calculations
V5

group a ;1 or group b ;2
type 1 or 2
V1

mean calibration factor                                  0.2596

standard deviation of the population                     0.0113

standard deviation of the mean                           0.0011

average of individual standard deviations                0.0047

after omitting values which deviate from the mean by
more than 3 sigma the new results are as follows,

mean calibration factor                                  0.2596

standard deviation of the population                     0.0113

standard deviation of the mean                           0.0011

mean internal background                                 2.3738

standard deviation of the population                     0.3257

standard deviation of the mean                           0.0326

average of individual standard deviations                0.1322

after omitting values which deviate from the mean by
more than 3 sigma the new results are as follows,

mean internal background                                 2.3555

standard deviation of the population                     0.2711

standard deviation of the mean                           0.0271
stop
time 2 secs.
```

the net dose rate. The program also lists the numbers of any dosimeters which deviate from the mean by more than two standard deviations. An example of a printout produced for a batch of ten dosimeters from Group B which were left in the field for a 730-hour monitoring period is reproduced in Table 7. The doses listed in the table are in mR and the dose rate, internal background, and net dose rate columns are in units of μR/hr.

A program of this nature eliminates a major source of human error and greatly facilitates the handling of data for a large scale environmental or laboratory investigation with the type of dosimeters studied here.

A second program, listed in Appendix E, was written to calculate and store TLD environmental surveillance measurements. The operator merely types in the number of the month, the hours the dosimeters were in the field and the TLD numbers and associated readings. Printouts can be obtained with a summary of data from each TLD at a location and the average and standard deviation for that location. The averages for a location for each of a number of months can also be obtained for annual reports or comparison purposes.

TIME-DEPENDENT FADING

The spontaneous decay of electrons from shallow traps at normal temperatures for different thermoluminescent materials has been observed previously and is well documented.(6,7) An investigation was conducted in an attempt to quantify this phenomenon for CaF_2:Mn.

Twenty-four dosimeters were chosen from group A and exposed to a known quantity of ^{226}Ra gamma rays and read out after a specific time interval. The measurements were repeated four times for each of a number of time intervals from 0.5 hours to 3 days. Each reading was corrected for the ambient background and the dosimeter's internal background. The readings were normalized by dividing the average corrected reading at 24 hours by the corrected reading at each other time period. This ratio gives a number to multiply the readings by in order to standardize the measurements at 24 hours. There was no need to convert the dose to mR, because each time the dosimeters were given the same dose.

Figure 4 and Table 8 show that fading is an exponential function of time, with most of the decay in the first 4 hours following exposure. Also, this investigation showed that fading is predictable and independent of the previous thermal or exposure history. Table 8 also includes fade information provided by the manufacturer, which compares well with the results of this investigation.

TABLE 7

COMPUTER PRINTOUT OF DOSE RATE CALCULATIONS

```
 what do you want to do?
code. . . 0=obtain a print out of calibration factor data
          1=add to or change calibration data
          2=obtain a print out of internal background data
          3=add to or change internal background data
          4=obtain a list of tld's,calibration factors,and internal bkgs.
          5=obtain statistical information on all tlds
          6=perform dose rate calculations
V6

enter the number of hours the tlds were in the field
V730


enter the number of tlds you have
V9


enter each of the tld numbers followed by its reading
V401,24.3 402,24.1 403,24.7 404,25.1 405,23.4 406,24.5

V407,28.3 408,24.1 409,25.0
```

tld	reading	cal fact	dose	dose rate	ib	net dose rate
401	24.30	0.318	7.73	10.59	1.87	8.71
402	24.10	0.337	8.13	11.14	1.93	9.21
403	24.70	0.326	8.04	11.02	1.98	9.04
404	25.10	0.328	8.22	11.26	1.93	9.33
405	23.40	0.322	7.55	10.34	1.85	8.49
406	24.50	0.325	7.97	10.92	1.99	8.93
407	28.30	0.327	9.27	12.69	1.97	10.73
408	24.10	0.331	7.98	10.93	1.87	9.06
409	25.00	0.327	8.18	11.20	1.96	9.24

```
mean net dose rate =    9.19 micro roentgen per hour

standard deviation =   0.634 micro roentgen per hour

the following tlds deviated from the mean by more than 2 sigma

tld407
stop
time 3 secs.
```

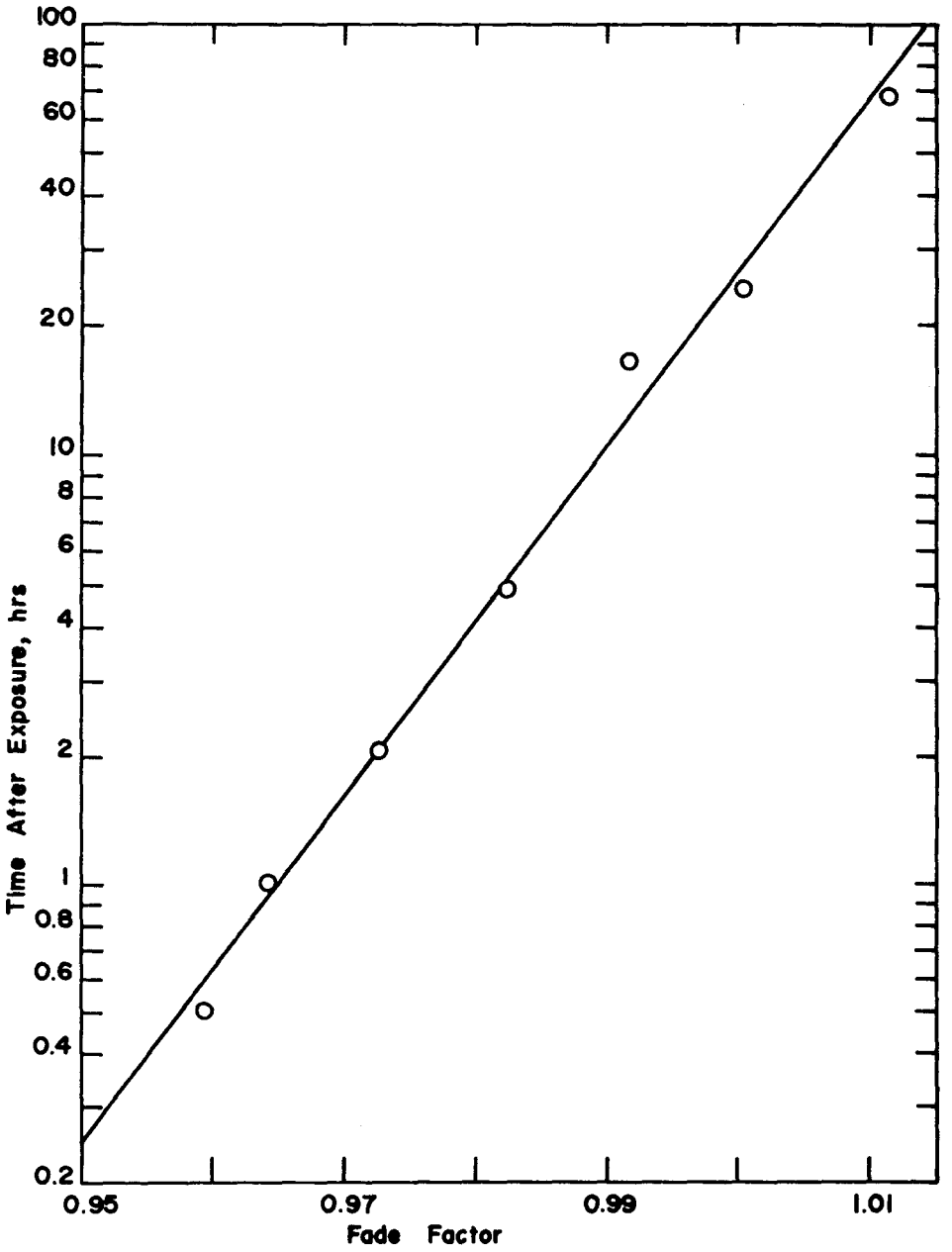


Figure 4 Time Dependent Fading

Table 8. Time-Dependent Fading

Time after exposure (hours)	R&NEB multiply reading by	Victoreen multiply reading by
.5	.959	.96
1.0	.964	.97
2.0	.972	.973
4.75	.982	.983
16.0	.991	.996
24.0	1.0	1.0
67.75	1.011	1.01

A second and even less stable electron trap was observed by delivering large doses (10 R - 15 R) to the dosimeters with a 0.1-Ci ^{60}Co source. The dosimeters were read out immediately after exposure. When the dosimeters were placed in the reader, they were observed to give off light even before the heating cycle was initiated. When the dosimeter was heated, the resulting glow curve had two distinct peaks. The first of these peaks. the low-temperature peak, was observed to decay at room temperature with a half life of less than 1 hour. Figure 5 shows a typical two-peak glow curve.

These results confirm the theory(4) that the main glow curve of CaF_2:Mn is really a composite curve formed by the superposition of multiple glow peaks which arise from a distribution of electron traps of different trapping characteristics. These traps of varying stability contribute to the measured height of the main glow peak and hence affect the reading if the dosimeter is read out before the low-temperature traps have had a chance to decay out.

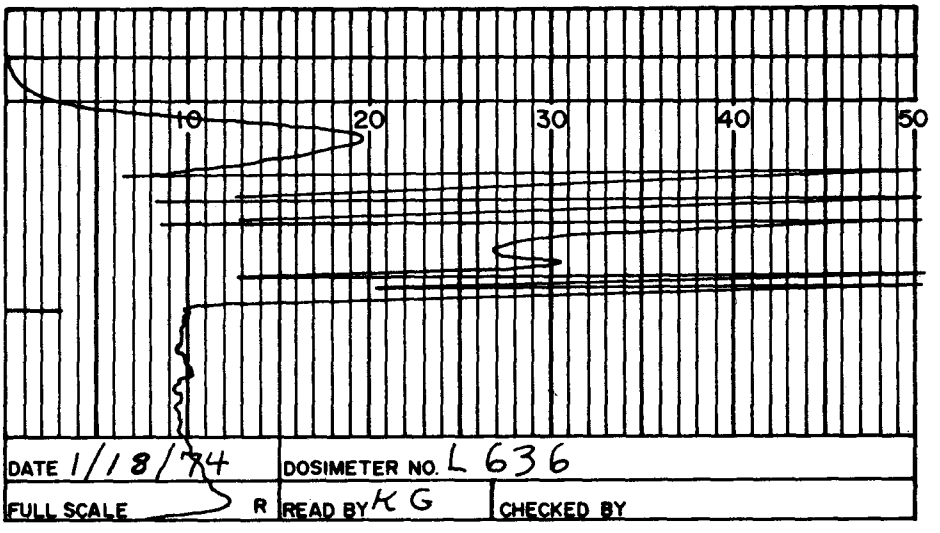


Figure 5 Two Peaked Glow Curve

Since practically all of the fading occurs within the first day, it was decided to allow at least 24 hours between exposure and readout for all dosimeter calibrations. Therefore, for environmental monitoring situations where the total dose is accumulated over a two to four week period, a fading correction is not necessary. The only conceivable situation in which a significant error could be introduced by this procedure would be in the case of a particularly high dose being received by the dosimeters immediately before they are picked up to be read out. The error in this case could amount to 5 percent if the dosimeters are read out within an hour. For environmental monitoring, this situation is considered unlikely.

LINEARITY

The linearity of response as a function of total exposure was investigated by exposing six random batches of 20-30 dosimeters from Group A to doses ranging from 0.9 mR to 12.5 mR, a typical range encountered in environmental monitoring situations. All exposures were from ^{226}Ra gamma rays.

The readings obtained were converted to mR values and the results were corrected for the internal background of the individual dosimeters. The mean values of the corrected data are plotted in Figure 6.

A least squares fit of the data yields a response versus exposure curve which is linear through zero with a standard deviation of 1.9 percent, which reflects the established reproducibility of the dosimeter-reader system.

EFFECTS OF EXPOSURE TO LIGHT

The fading rate of a dosimeter has been found to increase substantially when the unshielded detector is exposed to visible light. When exposed to office fluorescent light, the dosimeters have been observed to lose 4 percent of their readings in 20 minutes and 22 percent of their readings in 2 hours.

Exposure to sunlight, although not specifically studied here, has been observed(1) to effect a 40 percent reduction in dose in 5 minutes and 90 percent reduction in 10 minutes. It is, therefore, imperative that the detectors be left in their shields until they are read out.

Other effects, such as microwaves, ultraviolet and magnetic fields, ultrasonic fields, and mechanical vibrations have not been observed to affect the response of the dosimeters.

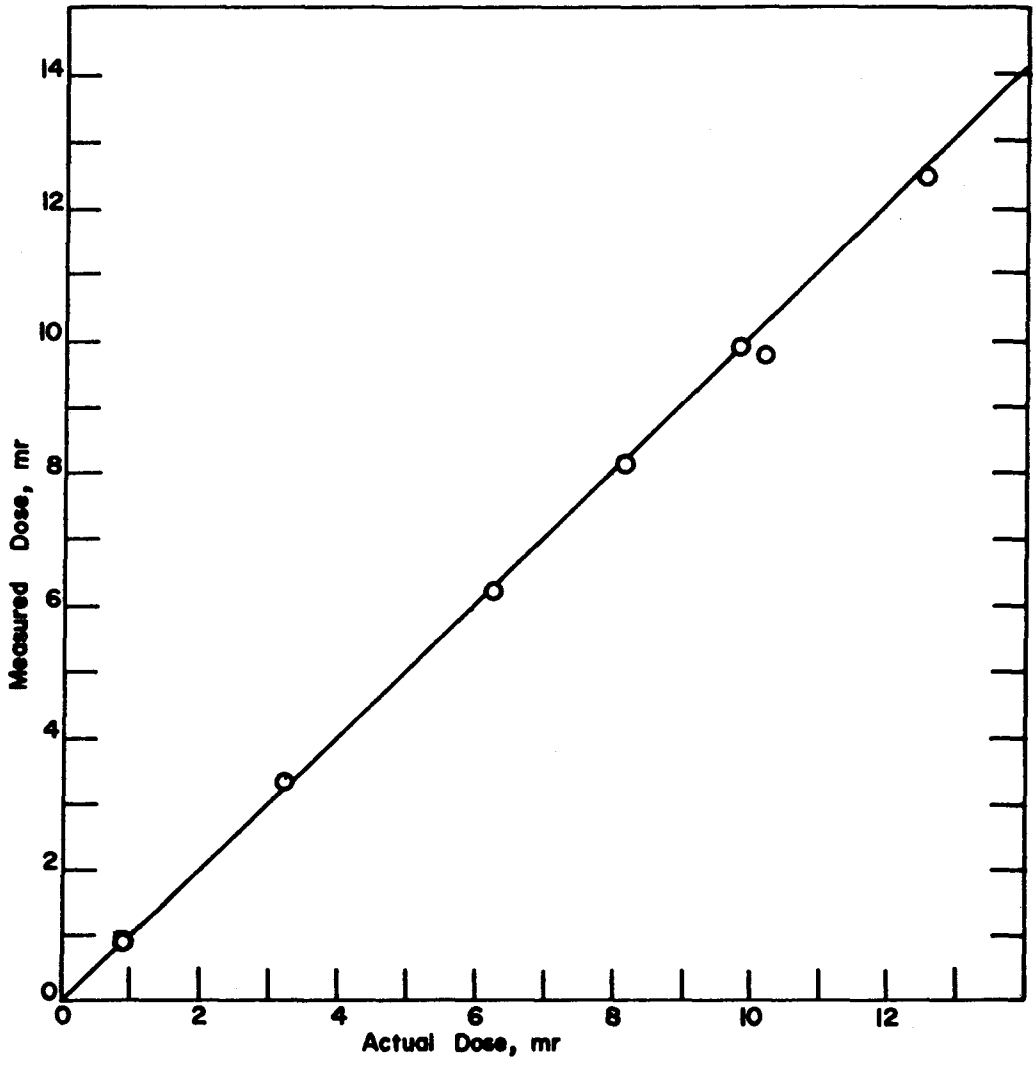


Figure 6 Linearity of Measured Dose vs. Actual Dose

SECTION V
ENVIRONMENTAL MONITORING RESULTS

After all parameters had been determined with sufficient accuracy in the laboratory, an environmental monitoring program was undertaken at the Vermont Yankee Nuclear Power Station (BWR) in Vernon, Vermont. A detailed report of this study has been prepared separately.(8) Results from the study indicate that the natural background exposure rate can be determined with a mean uncertainty (2σ) of 0.3 μR/hr. Fluctuations in the natural background due to snow cover on the ground can be observed and quantitated with TLD's, and increases in the exposure rate as small as 0.9 μR/hr due to plant operation are detectable.

SECTION VI
REFERENCES

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SECTION VII
APPENDICES

Appendix A. Theoretical Error in Calibration Factor Determination

Error in Readings (R)

Individual Errors

Zero Adjustment	0 ± 0.1 units
High Voltage	0 ± 0.23 units
Peak Height	37.5 ± 0.2 units

$$\sigma(R) = \sqrt{(0.1)^2 + (0.23)^2 + (0.2)^2} = 0.32 \text{ units}$$

i.e. R = 37.5 ± 0.32 units

Error in Source Strength at 50 cm (S)

Individual Errors

Distance (D)	50 ± 0.2 cm	
Radium Mass (M)	1.884 ± 0.038 gm	
Scattering Coefficient (S_c)	8.65×10^{-8} cm^{-2}	Effect is so small that error is negligible.
Attenuation Coefficient (A)	9.11×10^{-5} cm^{-1}	

$$S \text{ (mR/h)} = \frac{8.25 \times 10^3 \text{ M}}{D^2} (e^{-AD} + S_c D^2)$$

$$= \frac{8.25 \times 10^3 \times 1.884}{50^2} (e^{-9.11 \times 10^{-5} \times 50} + 8.65 \times 10^{-8} \times (50)^2)$$

$$= 6.190 \text{ mR/hr}$$

$$\{\sigma(S)\}^2 = \{\frac{8.25 \times 10^3}{D^2} (e^{-AD} + S_c D^2)\sigma(M)\}^2 + \left\{\{\frac{8.25 \times 10^3 M}{D^2} (-Ae^{-AD} + 2 S_c D) - \frac{2 \times 8.25 \times 10^3 \text{ M}}{D^3} (e^{-AD} + S_c D^2)\}\sigma(D)\right\}^2$$

$$= \left\{\frac{8.25 \times 10^3}{(50)^2} \{ e^{-9.11 \times 10^{-5} \times 50} + 8.65 \times 10^{-8} \times (50)^2\} \; 0.038\right\}^2$$

$$+ \left\{ \frac{8.25 \times 10^3 \times 1.884}{50^2} (- 9.11 \times 10^{-5} e^{-9.11 \times 10^{-5} \times 50} + 2 \times 8.65 \times 10^{-8} \times 50) - \frac{2 \times 8.25 \times 10^3 \times 1.884}{(50)^3} (e^{-9.11 \times 10^{-5} \times 50} + 8.65 \times 10^{-8} \times (50)^2)\ 0.2 \right\}^2$$

$= 0.01784$

$\sigma(S) = 0.134$ mR/hr

i.e. $S = 6.190 \pm 0.134$ mR/hr

<u>Error in Ambient Background (AB)</u>

Individual Errors

Time from annealing, through exposure, to placing in storage shield (T_{B1})	2.5 ± 0.5 hrs
Time from removing from storage to readout (T_{B2})	0.5 ± 0.25 hrs
Time in storage shield (T_s)	21 ± 1.0 hrs
Average background in shield (B_s)	2.00 ± 0.10 μR/hr
Average background outside shield (B_o)	9.0 ± 1.0 μR/hr

$AB = (T_{B1}) + T_{B2})B_o + T_s B_s$

$= (2.5 + 0.5)9 + 21 \times 2 = 69$ μR

$$\sigma(AB) = \sqrt{\{T_{B1}\sigma(B_o)\}^2 + \{B_o\sigma(T_{B1})\}^2 + \{T_{B2}\sigma(B_o)\}^2 + \{B_o\sigma(T_{B2})\}^2 + \{T_s\sigma(B_s)\}^2 + \{B_s\sigma(T_s)\}^2}$$

$$= \sqrt{(2.5 \times 1.0)^2 + (9.0 \times 0.5)^2 + (0.5 \times 1.0)^2 + (9.0 \times 0.25)^2 + (21 \times 0.1)^2 + (2.0 \times 1.0)^2}$$

$= 6.34$ μR

i.e. $AB = 0.069 \pm 0.0063$ mR

<u>Error in Internal Background (IB)</u>

From Appendix B,

$IB = 1.92 \pm 0.15$ μR/hr

or $= 0.046 \pm 0.004$ mR in 24 hrs.

Error in Calibration Factor (CF)

Individual Errors

Reading (R)	37.5 ± 0.32 units
Source Strength (S)	6.190 ± 0.134 mR/hr
Ambient Background (AB)	0.069 ± 0.0063 mR
Internal Background (IB)	0.046 ± 0.004 mR
Exposure Time (T)	1.438 ± 0.00278 hr

$$CF = \frac{ST + AB + IB}{R}$$

$$= \frac{6.190 \times 1.438 + 0.069 + 0.046}{37.5}$$

$$= 0.240 \text{ mR/unit}$$

$$(CF) = \sqrt{\{\frac{S}{R}\,\sigma(T)\}^2 + \{\frac{T}{R}\,\sigma(s)\}^2 + \{\frac{\sigma(AB)}{R}\}^2 + \{\frac{\sigma(IB)}{R}\}^2 + \{\frac{ST + AB + IB}{R^2}\,\sigma(R)\}^2}$$

$$= \sqrt{(\frac{6.190}{37.5} \times 2.78 \times 10^{-3})^2 + (\frac{1.438}{37.5} \times 1.34)^2 + (\frac{0.0063}{37.5})^2 + (\frac{0.004}{37.5})^2 + (\frac{6.190 \times 1.438 + 0.0069 + 0.046}{(37.5)^2} \times 0.32)^2}$$

$$= 5.6 \times 10^{-3} \text{ mR/unit}$$

i.e. CF = 0.240 + 0.0056 mR/unit

$$\frac{\sigma(CF)}{CF} = \frac{0.0056}{0.240} = 0.023 \text{ or } 2.3\%$$

Appendix B. Theoretical Error in Internal Background Measurements

Error in Reading (R)

Individual Errors

Zero Adjustment	$\pm$ 0.01 units
High Voltage	$\pm$ 0.023 units
Peak Height	2.80 $\pm$ 0.02 units

$$\sigma(R) = \sqrt{(0.01)^2 + (0.023)^2 + (0.02)^2} = 0.032 \text{ units}$$

i.e. R = 2.80 + 0.032 units

(Note that this error is a factor of 10 lower than that used in the calibration factor readings because the internal background measurements read out on a more sensitive reader scale.)

Error in Ambient Background (AB)

Time from annealing to placing in storage shield	1.0 hr
Time from removing from storage to readout	1.0 hr

Time = 2 $\pm$ 1 hrs

Average background in lab = 9 $\pm$ 1 μR/hr (7 $\pm$ 1 μR/hr above shield background)

$$\sigma(AB) = \sqrt{(7 \times 1)^2 + (2 \times 1)^2} = 7.3 \ \mu R$$

AB = 14 $\pm$ 7.3 μR

Error in Internal Background (IB)

Individual Errors

Calibration Factor (CF)	240 $\pm$ 5.6 μR/unit
Reading (R)	2.80 $\pm$ 0.032 units
Ambient Background (AB)	14 $\pm$ 7.3 μR

Shield Background (SB) 2.00 ± 0.10 μR/hr

Time (T) (Including two hours outside shield during annealing and reading) 168 ± 0.17 hrs

$$IB = \frac{R(CF)}{T} - \frac{AB}{T} - SB$$

$$= \frac{2.8(240)}{168} - \frac{14}{168} - 2.00 = 1.92 \quad R/hr$$

$$\sigma(IB) = \sqrt{\{\frac{R}{T}\,\sigma(CF)\}^2 + \{\frac{CF}{T}\,\sigma(R)\}^2 + \{\frac{\sigma(AB)}{T}\}^2 + \{\sigma(SB)\}^2 + \{\frac{R(CF) - AB}{T^2}\,\sigma(T)\}^2}$$

$$= \sqrt{(\frac{2.8}{168} \times 5.6)^2 + (\frac{240}{168} \times 0.032)^2 + (\frac{7.3}{168})^2 + (0.10)^2 + (\frac{2.8 \times 240 - 14}{(168)^2} \times 0.17)^2}$$

$$= 0.1507$$

i.e. $IB = 1.92 \pm 0.15$ μR/hr

$$\frac{\sigma(IB)}{IB} = \frac{0.15}{1.92} = 0.078 \text{ or } 7.8\%$$

Appendix C. Theoretical Error for Environmental Monitoring

Individual Errors

Reading (R)	25.0 ± 0.32 units
Calibration Factor (CF)	240 ± 5.6 μR/unit
Time (T)	700 ± 1 hr
Internal Background (IB)	1.92 ± 0.15 μR/hr

$$\text{Net Dose Rate} = \frac{R(CF)}{T} - IB$$

$$= \frac{(25)(240)}{700} - 1.92 = 6.65\ \mu R/hr$$

$$\sigma(\text{Net Dose Rate}) = \sqrt{\{\frac{R}{T}\,\sigma(CF)\}^2 + \{\frac{CF}{T}\,\sigma(R)\}^2 + \{\sigma(IB)\}^2 + \{\frac{R(CF)}{T^2}\,\sigma(T)\}^2}$$

$$= \sqrt{(\frac{25}{700} \times 5.6)^2 + (\frac{240}{700} \times 0.32)^2 + (0.15)^2 + (\frac{25 \times 240}{490{,}000} \times 1)^2}$$

$$= 0.273\ \mu R/hr$$

i.e. Net Dose Rate = 6.65 ± 0.27 μR/hr

$$\frac{\sigma(\text{Net Dose Rate})}{\text{Net Dose Rate}} = \frac{0.273}{6.65} = 0.041 \text{ or } 4.1\%$$

Appendix D. Program for Data Storage and Management of TLD Calibration Factors and Internal Backgrounds and for Performing Dose Rate Calculations

```
40 "THE PROGRAM IS DESIGNED TO STORE UP TO 15 CALIBRATION FACTORS "
50 "AND 15 INTERNAL BACKGROUNDS FOR 150 DOSIMETERS"
60
70 " THE PROGRAM USES SUBROUTINE STDEV WHICH ACCEPTS THE
80 "ONE DIMENSIONAL ARRAY X AS INPUT AND CALCULATES THE
90 "MEAN AND STANDARD DEVIATION OF THE ELEMENTS OF X"
100
110 REAL IB,MEAN,IB2,IB3,INTBKG,NDR(150),HOURS
120 DIMENSION READ(150),NO(150),DOSE(150),DR(150),J2(150)
130 DIMENSION AVGCF2(150),SIGCF2(150),INTBKG(150,15),NUMBR1(150),NU
MBR2(150)
140 DIMENSION IB(150,15),CF(150,15),MEAN(150)
150 DIMENSION SIGCF(150),AVGCF(150),CF2(150)
160 DIMENSION IB2(150),AVGIB2(150),NO2(150)
170 DIMENSION AVGIB(150),SIGIB(150),SIGIB2(150)
180 GO TO 75
190
200 " CF(N,M) = CALIBRATION FACTOR NUMBER M FOR TLD NUMBER N
210 " IB = INTERNAL BACKGROUND
220 " IB(N,M) = INTERNAL BACKGROUND NUMBER M FOR TLD NUMBER N
230 " NDR = NET DOSE RATE IN MICRO ■ PER HOUR
240 " HOURS = NUMBER OF HOURS TLDS ARE IN FIELD (FOR DOSE RATE
250 " CALCULATIONS)
260 " DOSE = TOTAL DOSE ON DOSIMETERS
270 " DR = DOSE RATE (DOSE/HOURS)
280 " AVGCF(N) = MEAN CALIBRATION FACTOR FOR TLD NUMBER N
290 " AVGCF2(N) = NEW MEAN, CALCULATED AFTER OMITTING VALUES WHICH
300 " DEVIATE FROM AVGCF(N) BY MORE THAN 3 STANDARD DEVIATIONS
310 " SIGCF(N) = STANDARD DEVIATION OF CALIBRATION FACTORS FOR TLD
320 " NUMBER N
330 " SIGCF2(N) = NEW STANDARD DEVIATION AFTER OMITTING VALUES
340 " WHICH DEVIATE FROM AVGCF(N) BY MORE THAN 3 STANDARD
350 " DEVIATIONS
360
370 2 WRITE(6,3)
380 3 FORMAT('+','WHAT DO YOU WANT TO DO■')
390 WRITE(6,58)
400 58 FORMAT(' ','CODE. . . 0=OBTAIN A PRINT OUT OF CALIBRATION FA
CTOR DATA')
410 WRITE(6,59)
420 59 FORMAT(' ',10X,'1=ADD TO OR CHANGE CALIBRATION DATA')
430 WRITE(6,660)
440 660 FORMAT(' ',10X,'2=OBTAIN A PRINT OUT OF INTERNAL BACKGROUND
 DATA')
450 WRITE(6,661)
460 661 FORMAT(' ',10X,'3=ADD TO OR CHANGE INTERNAL BACKGROUND DATA
')
```

```
470 WRITE(6,662)
480 662 FORMAT(' ',10X,'4=OBTAIN LIST OF TLD)S,CALIBRATION FACTORS,
 AND INTERNAL BKGS.')
490 WRITE(6,663)
500 663 FORMAT(' ',10X,'5=OBTAIN STATISTICAL INFORMATION ON ALL TLD
510 WRITE(6,664)
520 664 FORMAT(' ',10X,'6=PERFORM DOSE RATE CALCULATIONS')
530 "
540 " KKK IS READ IN AT EXECUTION TIME AND GIVES THE USER AN
550 " OPTION AS TO WHICH SECTION OF THE PROGRAM HE WISHES TO USE
560 "
570 75 READ(5,*) KKK
580 IF(KKK.EQ.0) GO TO 222
590 IF(KKK.EQ.1) GO TO 76
600 IF(KKK.EQ.2) GO TO 222
610 IF(KKK.EQ.3) GO TO 222
620 IF(KKK.EQ.4) GO TO 222
630 IF(KKK.EQ.5) GO TO 222
640 IF(KKK.EQ.6) GO TO 222
650 WRITE(6,77)
660 77 FORMAT('+','TRY AGAIN FUMBLE FINGERS')
670 GO TO 75
680
690 " THIS SECTION OF THE PROGRAM IS USED FOR ADDING A NEW GROUP
700 " OF CALIBRATION FACTORS OR FOR CHANGING ANY PREVIOUSLY STORED
DATA
710
720 76 CONTINUE
730 100 FORMAT(' ','NEW GROUP OF DATA (1), CHANGE EXISTING DATA (2)
')
740 WRITE(6,100)
750 WRITE(6,102)
760 102 FORMAT(' ','TYPE 1 OR 2')
770 105 READ(5,*) KK
780 IF(KK.EQ.2) GO TO 103
790 IF(KK.EQ.1) GO TO 104
800 WRITE(6,77)
810 GO TO 105
820
830 " ALL CALIBRATION FACTORS FROM DATA FILE KG ARE READ IN
840
850 104 CALL OPEN(2,'NAM1','INPUT')
860 READ(2,*) ((CF(N,M),M=1,15),N=1,150)
870 908 CALL CLOSE(2)
880
890 " THE PROGRAM SORTS THROUGH THE READINGS FOR EACH DOSIMETER"
900 " UNTIL A ZERO READING IS FOUND, THEN READS IN A NEW CALIBRATIO
N"
910 " FACTOR FOR THAT DOSIMETER AND REPLACES THE ZERO READING WITH
IT."
920
930 WRITE(6,320)
940 320 FORMAT(' ','ENTER EACH TLD NUMBER AND ITS CAL. FACT.','/' WH
EN DONE, TYPE 0,0')
950 824 READ(5,*) N,X
951 IF(N.GT.150) GO TO 10
952 IF(N.EQ.0) GO TO 10
```

```
960 CALL NUMBER(N,N1)
970 N=N1
1000 DO 822 M=1,15
1010 IF(CF(N,M).EQ.0.) GO TO 823
1020 822 CONTINUE
1030 823 CF(N,M)=X
1040 GO TO 824
1130 110 FORMAT(' ','TYPE IN N,M,AND X. . .WHERE N IS THE NUMBER OF
 THE TLD, M IS THE NUMBER')
1140
1150 " THIS SEGMENT ENABLES THE USER TO REPLACE ANY INDIVIDUAL "
1160 " READING FOR ANY DOSIMETER BY TYPING IN THE NUMBER OF THE TLD
,"
1170 " THE NUMBER OF THE READING TO BE REPLACED, AND THE NEW C.F."
1180
1190 103 WRITE(6,110)
1200 WRITE(6,112)
1210 112 FORMAT(' ','OF THE READING YOU WISH TO REPLACE, AND X IS T
HE NEW CALIBRATION FACTOR')
1220 WRITE(6,113)
1230 113 FORMAT(' ','THEN HIT RETURN.  REPEAT FOR AS MANY TLDS AS Y
OU LIKE. ')
1240 WRITE(6,114)
1250 114 FORMAT(' ',' WHEN DONE, HIT RETURN AND TYPE 0,0,0')
1260
1270 " ALL CALIBRATION NUMBERS ARE READ IN FROM DATA FILE KG
1280
1290 CALL OPEN(2,'NAM1','INPUT')
1300 READ(2,*) ((CF(N,M),M=1,15),N=1,150)
1310 CALL CLOSE(2)
1320 120 READ(5,*) NN,MM,XX
1350
1360 " NN = NUMBER OF TLD
1370 " MM = NUMBER OF CALIBRATION FACTOR YOU WISH TO CHANGE
1380 " XX = NEW CALIBRATION FACTOR
1390
1400 IF(NN.EQ.0) GO TO 10
1410 IF(MM.EQ.0) MM=15
1420 IF(MM.GT.15) MM=15
1421 CALL NUMBER(NN,N1)
1422 NN=N1
1430 CF(NN,MM) = XX
1440 GO TO 120
1450 10 CONTINUE
1460
1470 " ALL NEW DATA IS NOW WRITTEN ON DATA FILE KG
1480
1490 CALL OPEN(2,'NAM1','OUTPUT')
1500 WRITE(2,*) ((CF(N,M),M=1,15),N=1,150)
1510 CALL CLOSE(2)
1520 IF(KKK.EQ.1) STOP
1530 222 CONTINUE
```

```
1540
1550 " READ IN ALL CALIBRATION FACTORS FROM DATA FILE KG"
1560
1570 CALL OPEN(2,'NAM1','INPUT')
1580 READ(2,*) ((CF(N,M),M=1,15),N=1,150)
1590 CALL CLOSE(2)
1600
1610 " COUNT THE NUMBER OF CALIBRATION FACTORS FOR EACH DOSIMETER
1620 " AND SET THE NUMBER EQUAL TO J
1630
1640 DO 15 N=1,150
1650 DO 133 JJ=1,15
1660 IF(CF(N,JJ).NE.0.) GO TO 14
1670 J=JJ-1
1680 GO TO 933
1690 14 CF2(JJ)=CF(N,JJ)
1700 J=JJ
1710 133 CONTINUE
1720 933 CONTINUE
1730
1740 " FIND THE AVERAGE CALIBRATION FACTOR FOR EACH DOSIMETER
1750 " SET AVERAGE EQUAL TO AVGCF(N) AND STANDARD DEVIATION EQUAL T
O SIGCF(N)
1760
1770 CALL STDEV(CF2,J,AVG,SIGMA)
1780 AVGCF(N)=AVG
1790 SIGCF(N)=SIGMA
1800 K=1
1810 DO 31 KK=1,J
1820
1830 " CALCULATE DD, THE DEVIATION FROM THE MEAN FOR EACH CALIBRATI
ON FACTOR
1840
1850 DD=ABS(CF2(KK)-AVGCF(N))
1860 IF(DD.GE.3*SIGCF(N)) GO TO 31
1870 CF2(K)=CF2(KK)
1880 K=K+1
1890 31 CONTINUE
1900
1910 " CF2 NOW REPRESENTS ALL CALIBRATION FACTORS FOR TLD N WHICH D
O
1920 " NOT DEVIATE FROM THE MEAN BY MORE THAN 3 STANDARD DEVIATIONS
1930 " NOW FIND A NEW MEAN FOR CF2, SET THE NEW MEAN EQUAL TO AVGCF
2(N),
1940 " AND SET THE NEW STANDARD DEVIATION EQUAL TO SIGCF2(N)
1950 "
1960 CALL STDEV(CF2,K-1,AVG,SIGMA)
1970 AVGCF2(N)=AVG
1980 SIGCF2(N)=SIGMA
1990 NUMBR1(N)=J
2000 15 CONTINUE
2010 "
```

```
2020 " NOW FIND THE MEAN OF THE AVERAGE CALIBRATION FACTORS FOR
2030 " THE ENTIRE BATCH AND SET THIS MEAN EQUAL TO AVGTOT
2040 " THEN FIND THE MEAN OF THE INDIVIDUAL STANDARD DEVIATIONS
2050 " AND SET THIS EQUAL TO AVGSIG1
2060 " FINALLY, CALCULATE THE STANDARD DEVIATION OF THE POPULATION
2070 " AND SET THIS EQUAL TO SM
2080
2090 IF(KKK.NE.5) GO TO 406
2100 WRITE(6,400)
2110 400 FORMAT(' ','GROUP A (1) OR GROUP B (2)',/,' TYPE 1 OR 2')
2120 403 READ(5,*) K3
2130 IF(K3.EQ.1) GO TO 401
2140 IF(K3.EQ.2) GO TO 402
2150 WRITE(6,77)
2160 GO TO 403
2170 401 N1=51
2180 N2=150
2190 DO 410 N=1,100
2200 N3=N+50
2210 AVGCF2(N)=AVGCF2(N3)
2220 410 SIGCF2(N)=SIGCF2(N3)
2230 CALL STDEV(AVGCF2,N,AVGTOT,SIGTOT)
2240 CALL STDEV(SIGCF2,N,AVSIG1,S)
2250 SM=SIGTOT/SQRT(FLOAT(N))
2260 GO TO 405
2270 402 N1=1
2280 N2=50
2290 N=50
2300 CALL STDEV(AVGCF2,N,AVGTOT,SIGTOT)
2310 CALL STDEV(SIGCF2,N,AVSIG1,S)
2320 SM=SIGTOT/SQRT(FLOAT(N))
2330 L=1
2340
2350 " CALCULATE D, THE DEVIATION FROM THE MEAN FOR EACH TLD
2360 " AND OMIT VALUES WHICH DEVIATE BY MORE THAN 3 SIGMA
2370 " THEN CALCULATE A NEW MEAN, STANDARD DEVIATION OF THE
2380 " NEW MEAN, AND THE STANDARD DEVIATION OF THE NEW POPULATION
2390
2400 DO 85 N=1,50
2410 D=ABS(AVGCF2(N)-AVGTOT)
2420 IF(D.GE.3*SIGTOT) GO TO 85
2430 CF2(L)=AVGCF2(N)
2440 L=L+1
2450 85 CONTINUE
2460 CALL STDEV(CF2,L-1,AVGT2,SIGT2)
2470 SM2=SIGT2/SQRT(FLOAT(L))
2480 GO TO 406
2490 405 CONTINUE
2500 L=1
2510 DO 407 N=1,100
2520 AVGCF2(N3)=AVGCF2(N)
2530 SIGCF2(N3)=SIGCF2(N)
```

```
2540 D=ABS(AVGCF2(N)-AVGTOT)
2550 IF(D.GE.3*SIGTOT) GO TO 407
2560 CF2(L)=AVGCF2(N3)
2570 L=L+1
2580 407 CONTINUE
2590 CALL STDEV(CF2,L-1,AVGT2,SIGT2)
2600 SM2=SIGT2/SQRT(FLOAT(L))
2610 406 CONTINUE
2620 IF(KKK.EQ.2) GO TO 225
2630 IF(KKK.EQ.3) GO TO 520
2640 IF(KKK.EQ.4) GO TO 225
2650 IF(KKK.EQ.6) GO TO 225
2660 IF(KKK.EQ.5) GO TO 225
2670
2680 " THIS SEGMENT OF THE PROGRAM PRINTS OUT ALL CALIBRATION FACTO
R DATA
2690
2700 756 WRITE(6,755)
2710 755 FORMAT(' ','PRINTOUT FOR GROUP |1&, OR INDIVIDUALS |2&')
2720 WRITE(6,102)
2730 READ(5,*) K3
2740 IF(K3.EQ.2) GO TO 759
2750 IF(K3.EQ.1) GO TO 757
2760 WRITE(6,77)
2770 GO TO 756
2780 759 CONTINUE
2790 WRITE(6,760)
2800 760 FORMAT(' ','ENTER THE NUMBER OF TLDS YOU WANT PRINTED OUT'
)
2810 READ(5,*) NO1
2820 WRITE(6,761)
2830 761 FORMAT(' ','ENTER THE NUMBERS OF THE TLDS')
2840 READ(5,*) (NO2(I),I=1,NO1)
2850 DO 752 N=1,NO1
2860 CALL NUMBER(NO2(N),L)
2870 NUM=NUMBR1(L)
2880 WRITE(6,753) NO2(N),(CF(L,M),M=1,NUM)
2890 753 FORMAT('0',I3,7F9.4,/,4X,7F9.4)
2900 752 CONTINUE
2910 STOP
2920 757 CONTINUE
2930 WRITE(6,920)
2940 920 FORMAT(' ','YOU WILL GET A PRINT OUT FOR TLDS N THRU M')
2950 WRITE(6,121)
2960 121 FORMAT(' ','ENTER N AND M')
2970 READ(5,*) N1,N2
2980 CALL NUMBER(N1,N4)
2990 N1=N4
3000 CALL NUMBER(N2,N5)
3010 N2=N5
3020 WRITE(6,43)
3030 43 FORMAT(' ','TLD'3X'CAL FACT'3X'MEAN'5X'SIGMA'3X'NEW MEAN'3X
'NEW SIGMA')
```

```
3040 DO 52 N=N1,N2
3050 CALL NUMB2(N,N7)
3060 WRITE(6,42)N7,CF(N,1),AVGCF(N),SIGCF(N),AVGCF2(N),SIGCF2(N)
3070 42 FORMAT(' ',I3,F9.3,F10.3,F9.3,2F10.3)
3080 NUM=NUMBR1(N)
3090 DO 52 M=2,NUM
3100 WRITE(6,41) CF(N,M)
3110 41 FORMAT(' ',6X,F6.3)
3120 52 CONTINUE
3130 IF(KKK.EQ.0) STOP
3140 IF(KKK.EQ.1) STOP
3150
3160 " THIS SEGMENT OF THE PROGRAM ALLOWS THE USER TO ADD TO OR
3170 " CHANGE THE INTERNAL BACKGROUND DATA
3180
3190 520 WRITE(6,100)
3200 WRITE(6,102)
3210 130 READ(5,*) KK
3220 IF(KK.EQ.2) GO TO 131
3230 IF(KK.EQ.1) GO TO 132
3240 WRITE(6,77)
3250 GO TO 130
3260 "
3270 " IF THE USER WANTS TO ADD A NEW GROUP OF DATA, ALL THE DATA
3280 " FROM FILE IB ARE FIRST READ IN AND THE NEW READINGS ARE
3290 " INSERTED.  THE DATA IS THEN REWRITTEN ONTO FILE IB
3300 "
3310 132 CALL OPEN(3,'IB','INPUT')
3320 READ(3,*) ((IB(N,M),M=1,15),N=1,150)
3330 1033 CALL CLOSE(3)
3340 WRITE(6,431)
3350 431 FORMAT(' ','ENTER THE NUMBER OF HOURS THE TLDS WERE IN THE
 FIELD')
3360 READ(5,*) HOURS
3370 WRITE(6,430)
3380 430 FORMAT(' ','ENTER EACH TLD NUMBER AND ITS READING,'/' WHEN
 DONE,TYPE 0,0')
3390 432 READ(5,*) N,X
3400 CALL NUMBER(N,N1)
3410 N=N1
3420 IF(N.GT.150) GO TO 134
3430 IF(N.EQ.0) GO TO 50
3440 DO 135 M=1,15
3450 IF(IB(N,M).EQ.0.) GO TO 136
3460 135 CONTINUE
3470 136 IB(N,M)=X*1000/HOURS
3480 GO TO 432
3490 134 WRITE(6,433)
3500 433 FORMAT(' ','TLD NUMBER TOO BIG, TRY AGAIN')
3510 GO TO 432
3520
3530 " HERE THE USER CAN CHANGE INDIVIDUAL DATA POINTS BY ENTERING
```

```
3540 " THE NUMBER OF THE TLD, THE NUMBER OF THE READING TO BE
3550 " REPLACED, AND THE NEW READING
3560 "
3570 131 WRITE(6,110)
3580 WRITE(6,772)
3590 772 FORMAT(' ','OF THE READING YOU WANT REPLACED, AND X IS THE
 NEW INTERNAL BACKGROUND')
3600 WRITE(6,113)
3610 WRITE(6,114)
3620 CALL OPEN(3,'IB','INPUT')
3630 READ(3,*) ((IB(N,M),M=1,15),N=1,150)
3640 CALL CLOSE(3)
3650 137 READ(5,*) NN,MM,XX
3660 CALL NUMBER(NN,N1)
3670 NN=N1
3680 IF(NN.EQ.0) GO TO 50
3690 IF(MM.EQ.0) MM=15
3700 IB(NN,MM)=(XX+2.)/AVGCF2(NN)
3710 IF(XX.EQ.0.) IB(NN,MM)=0.
3720 GO TO 137
3730 50 CONTINUE
3740
3750 " ALL NEW INTERAL BACKGROUND DATA IS WRITTEN OF FILE IB
3760
3770 CALL OPEN(3,'IB','OUTPUT')
3780 WRITE(3,*) ((IB(N,M),M=1,15),N=1,150)
3790 CALL CLOSE(3)
3800 STOP
3810 225 CONTINUE
3820
3830 " THE INTERNAL BACKGROUND DATA ARE READ IN AND THE STANDARD
3840 " DEVIATIONS FOR EACH DOSIMETER ARE CALCULATED
3850
3860 CALL OPEN(3,'IB','INPUT')
3870 READ(3,*,END=777) ((IB(N,M),M=1,15),N=1,150)
3880 777 CONTINUE
3890 CALL CLOSE(3)
3900 DO 61 N=1,150
3910 DO 62 JJ=1,15
3920 IF(IB(N,JJ).NE.0.) GO TO 63
3930 J=JJ-1
3940 GO TO 962
3950 63 INTBKG(N,JJ)=IB(N,JJ)*AVGCF2(N)-2.
3960 IB2(JJ)=INTBKG(N,JJ)
3970 J=JJ
3980 62 CONTINUE
3990 962 CONTINUE
4000 CALL STDEV(IB2,J,AVG,SIGMA)
4010 AVGIB(N)=AVG
4020 SIGIB(N)=SIGMA
4030 K=1
4040
```

```
4050 " THE DEVIATION FROM THE MEAN IS CALCULATED AND ALL READINGS
4060 " WHICH DEVIATE FROM THE MEAN BY MORE THAN 3 SIGMA ARE LEFT OU
T
4070 " A NEW MEAN AND A NEW STANDARD DEVIATION ARE THEN CALCULATED
4080
4090 " THE NEW MEAN IS SET EQUAL TO AVGIB2 AND THE NEW STANDARD
4100 " DEVIATION IS SET EQUAL TO SIGIB2
4110
4120 DO 64 KK=1,J
4130 D=ABS(IB2(KK)-AVGIB(N))
4140 IF(D.GE.3*SIGIB(N)) GO TO 640
4150 IB2(K)=IB2(KK)
4160 K=K+1
4170 640 CONTINUE
4180 64 CONTINUE
4190 CALL STDEV(IB2,K-1,AVG,SIGMA)
4200 AVGIB2(N)=AVG
4210 SIGIB2(N)=SIGMA
4220 NUMBR2(N)=J
4230 61 CONTINUE
4240
4250 " NOW THE STANDARD DEVIATION OF THE ENTIRE POPULATION IS
4260 " CALCULATED AND SET EQUAL TO AVGT3 AND THE STANDARD
4270 " DEVIATION OF THE INDIVIDUAL STANDARD DEVIATIONS (IF YOU
4280 " CAN DIG THAT) IS CALCULATED AND SET EQUAL TO AVSIG2
4290
4300 IF(K3.EQ.2) GO TO 408
4310 IF(KKK.NE.5) GO TO 436
4320 N1=51
4330 N2=150
4340 DO 409 N=1,100
4350 N3=N+50
4360 AVGIB2(N)=AVGIB2(N3)
4370 SIGIB2(N)=SIGIB2(N3)
4380 409 CONTINUE
4390 CALL STDEV(AVGIB2,N,AVGT3,SIGT3)
4400 CALL STDEV(SIGIB2,N,AVSIG2,S)
4410 SM3=SIGT3/SQRT(FLOAT(N))
4420 LL=1
4430 DO 411 N=1,100
4440 D=ABS(AVGIB2(N)-AVGT3)
4450 AVGIB2(N3)=AVGIB2(N)
4460 SIGIB2(N3)=SIGIB2(N)
4470 IF(D.GE.3*SIGT3) GO TO 411
4480 IB2(LL)=AVGIB2(N3)
4490 LL=LL+1
4500 411 CONTINUE
4510 CALL STDEV(IB2,LL-1,AVGT4,SIGT4)
4520 SM4=SIGT4/SQRT(FLOAT(LL))
4530 GO TO 412
4540 408 N=50
4550 CALL STDEV(AVGIB2,N,AVGT3,SIGT3)
```

```
4560 CALL STDEV(SIGIB2,N,AVSIG2,S)
4570 SM3=SIGT3/SQRT(FLOAT(N))
4580 LL=1
4590 DO 88 N=1,50
4600
4610 " AGAIN, THE DEVIATION FROM THE MEAN IS CALCULATED AND THE
4620 " NUMBERS WHICH DEVIATE BY MORE THAN 3 SIGMA ARE TEMPORARALLY
4630 " OMITTED AND A NEW MEAN AND STANDARD DEVIATION IS CALCULATED
4640
4650 D=ABS(AVGIB2(N)-AVGT3)
4660 IF(D.GE.3*SIGT3) GO TO 88
4670 IB2(LL)=AVGIB2(N)
4680 LL=LL+1
4690 88 CONTINUE
4700 CALL STDEV(IB2,LL-1,AVGT4,SIGT4)
4710 SM4=SIGT4/SQRT(FLOAT(LL))
4720 412 CONTINUE
4730 436 CONTINUE
4740 IF(KKK.EQ.4) GO TO 70
4750 IF(KKK.EQ.6) GO TO 311
4760 IF(KKK.EQ.5) GO TO 80
4770
4780 " THIS SECTION OF THE PROGRAM PRINTS OUT ALL INTERNAL BACKGROU
ND
4790 " DATA.  THE USER CAN PRINT OUT ANY SUBGROUP OF DATA FROM
4800 " TLD N1 THROUGH TLD N2
4810
4820 " TLD
4830 766 WRITE(6,755)
4840 WRITE(6,102)
4850 READ(5,*) K3
4860 IF(K3.EQ.2) GO TO 769
4870 IF(K3.EQ.1) GO TO 767
4880 WRITE(6,77)
4890 " TLD N1 THROUGH TLD N2
4900 GO TO 766
4910 769 CONTINUE
4920 WRITE(6,760)
4930 READ(5,*) NO1
4940 WRITE(6,761)
4950 READ(5,*) (NO2(I),I=1,NO1)
4960 DO 762 N=1,NO1
4970 CALL NUMBER(NO2(N),L)
4980 NUM=NUMBR2(L)
4990 WRITE(6,753) NO2(N),(INTBKG(L,M),M=1,NUM)
5000 762 CONTINUE
5010 STOP
5020 767 CONTINUE
5030 WRITE(6,920)
5040 WRITE(6,121)
5050 READ(5,*) N1,N2
5060 CALL NUMBER(N1,N4)
```

```
5070 N1=N4
5080 CALL NUMBER(N2,N5)
5090 N2=N5
5100 IF(N2.GE.150) N2=150
5110 WRITE(6,83)
5120 83 FORMAT(' ','TLD'3X'INT BKG'4X'MEAN'5X'SIGMA'3X'NEW MEAN'2X'
NEW SIGMA')
5130 DO 71 N=N1,N2
5140 CALL NUMB2(N,N9)
5150 WRITE(6,42) N9,INTBKG(N,1),AVGIB(N),SIGIB(N),AVGIB2(N),SIGIB2(
N)
5160 NUM2=NUMBR2(N)
5170 DO 71 M=2,NUM2
5180 WRITE(6,41) INTBKG(N,M)
5190 71 CONTINUE
5200 70 CONTINUE
5210
5220 " CALIBRATION FACTORS AND INTERNAL BACKGROUNDS IN TABULAR
5230 " FORM FOR TLDS N THROUGH M.  IT ALSO PRINTS OUT THE NUMBER
5240 " OF READINGS STORED IN MEMORY FOR EACH DOSIMETER.
5250
5260 IF(KKK.NE.4) STOP
5270 WRITE(6,920)
5280 WRITE(6,121)
5290
5300 " N1 AND N2 ARE READ IN
5310
5320 READ(5,*) N1,N2
5330 CALL NUMBER(N1,N4)
5340 CALL NUMBER(N2,N5)
5350 N1=N4
5360 N2=N5
5370 WRITE(6,151)
5380 151 FORMAT(' ',24X,'NUMBER OF',20X,'NUMBER OF')
5390 WRITE(6,81)
5400 81 FORMAT(' ','TLD',2X,'CAL. FACT.',2X,'SIGMA',2X,'READINGS',4
X,'INT. BKG',2X,'SIGMA',2X,'READINGS')
5410 DO 80 N=N1,N2
5420 CALL NUMB2(N,N8)
5430 WRITE(6,82) N8,AVGCF2(N),SIGCF2(N),NUMBR1(N),AVGIB2(N),SIGIB2(
N),NUMBR2(N)
5440 82 FORMAT(' ',I3,F10.3,F10.3,I6,F13.2,F10.3,I6)
5450 80 CONTINUE
5460
5470 " THIS SECTION OF THE PROGRAM PRINTS OUT ALL STATISTICAL
5480 " INFORMATION ON THE TWO GROUPS OF DOSIMETERS.  SUCH INFOR-
5481 " MATION AS THE AVERAGE CALIBRATION FACTOR AND AVERAGE
5490 " INTERNAL BACKGROUND FOR THE ENTIRE BATCH OF DOSIMETERS
5500 " IS PRINTED OUT.
5510
5520 IF(KKK.NE.5) STOP
5530 WRITE(6,84) AVGTOT
```

```
5540 84 FORMAT('0',/,' MEAN CALIBRATION FACTOR=', T50,F7.4)
5550 WRITE(6,86) SIGTOT
5560 86 FORMAT('0','STANDARD DEVIATION OF THE POPULATION=',T50,F7.4
)
5570 WRITE(6,87) SM
5580 87 FORMAT('0','STANDARD DEVIATION OF THE MEAN=',T50,F7.4)
5590 WRITE(6,150) AVSIG1
5600 150 FORMAT('0','AVERAGE OF INDIVIDUAL STANDARD DEVIATIONS=',T5
0,F7.4)
5610 WRITE(6,888)
5620 888 FORMAT('0',/,' AFTER OMITTING VALUES WHICH DEVIATE FROM TH
E MEAN BY ')
5630 WRITE(6,94)
5640 WRITE(6,84) AVGT2
5650 WRITE(6,86) SIGT2
5660 WRITE(6,87) SM2
5670 WRITE(6,90) AVGT3
5680 90 FORMAT('0',/,' MEAN INTERNAL BACKGROUND=',T50,F7.4)
5690 WRITE(6,86) SIGT3
5700 91 FORMAT('0','STANDARD DEVIATION OF THE POPULATION=',F5.2)
5710 WRITE(6,87)  SM3
5720 92 FORMAT('0','STANDARD DEVIATION OF THE MEAN=',F5.2)
5730 WRITE(6,150) AVSIG2
5740 WRITE(6,888)
5750 WRITE(6,94)
5760 94 FORMAT(' ','MORE THAN 3 SIGMA THE NEW RESULTS ARE AS FOLLOW
S,')
5770 WRITE(6,90) AVGT4
5780 WRITE(6,86) SIGT4
5790 WRITE(6,87) SM4
5800 311 CONTINUE
5810 IF(KKK.EQ.5) STOP
5820
5830 " THIS SEGMENT OF THE PROGRAM PERFORMS DOSE RATE CALCULATIONS
5840 " THE NUMBER OF HOURS THE TLDS WERE IN THE FIELD AND ALL OF TH
E
5850 " READINGS FOR A BATCH OF TLDS ARE READ IN AS INPUT AND THE
5860 " PROGRAM CALCULATES THE TOTAL DOSE, THE TOTAL DOSE RATE, AND
5870 " THE NET DOSE RATE.
5880
5890
5900 WRITE(6,312)
5910 312 FORMAT(' ','ENTER THE NUMBER OF HOURS THE TLDS WERE IN THE
 FIELD')
5920 READ(5,*) HOURS
5930 WRITE(6,316)
5940 316 FORMAT('0','ENTER THE NUMBER OF TLDS YOU HAVE')
5950 READ(5,*) N3
5960 WRITE(6,317)
5970 317 FORMAT('0','ENTER EACH OF THE TLD NUMBERS FOLLOWED BY ITS
READING')
```

```
5980 READ(5,*) (NO(NN),READ(NN),NN=1,N3)
5990 DO 827 I3=1,N3
6000 CALL NUMBER(NO(I3),N6)
6010 827 NO(I3)=N6
6020 N3=N3+1
6030 DO 300 NN=1,N3
6040 IF(NO(NN).EQ.0) GO TO 301
6050 DOSE(NN)=READ(NN)*AVGCF2(NO(NN))
6060 DR(NN)=1000*DOSE(NN)/HOURS
6070 NDR(NN)=DR(NN)-AVGIB2(NO(NN))
6080 300 CONTINUE
6090 301 WRITE(6,303)
6100 303 FORMAT(' ',' TLD',3X'READING',3X,'CAL FACT',4X'DOSE',4X,'D
OSE RATE',5X,'IB',5X'NET DOSE RATE')
6110 NN2=NN-1
6120 DO 302 N=1,NN2
6130 CALL NUMB2(NO(N),N7)
6140 WRITE(6,304)N7,READ(N),AVGCF2(NO(N)),DOSE(N),DR(N),AVGIB2(NO(N
)),NDR(N)
6150 302 CONTINUE
6160 304 FORMAT(' ',I3,4X,F6.2,5X,F6.3,3X,F6.2,5X,F7.2,5X ,F4.2,5X
 ,F7.2)
6170
6180 " THE AVERAGE NET DOSE RATE AND THE STANDARD DEVIATION ARE
6190 " ARE CALCULATED
6200
6210 CALL STDEV(NDR,NN2,A,S)
6220 J=1
6230 DO 305 N=1,NN2
6240
6250 " ANY READINGS WHICH DEVIATE FROM THE MEAN BY MORE THAN 2
6260 " STANDARD DEVIATIONS ARE LOCATED AND PRINTED OUT
6270
6280 D=ABS(NDR(N)-A)
6290 IF(D.LE.2*S) GO TO 305
6300 J2(J)=NO(N)
6310 J=J+1
6320 305 CONTINUE
6330 WRITE(6,314) A
6340 WRITE(6,315) S
6350 315 FORMAT('0','STANDARD DEVIATION *',F8.3,' MICRO ROENTGEN PE
R HOUR')
6360 307 FORMAT('0','TLD',I3)
6370 K=J-1
6380 WRITE(6,308)
6390 308 FORMAT('0','THE FOLLOWING TLDS DEVIATED FROM THE MEAN BY M
ORE THAN 2 SIGMA')
6400 IF(K.EQ.0) GO TO 309
6410 DO 306 I=1,K
6415 CALL NUMB2(J2(I),I5)
6420 WRITE(6,307) I5
```

```
6430 306 CONTINUE
6440 STOP
6450 309 WRITE(6,310)
6460 310 FORMAT('0','NONE')
6470 314 FORMAT('0','MEAN NET DOSE RATE *',F8.2,' MICRO ROENTGEN PE
R HOUR')
6480 STOP
6490 END
6500 SUBROUTINE STDEV(X,J,AVG,SIGMA)
6510
6520 " THIS SUBROUTINE ACCEPTS A ONE DIMENSIONAL ARRAY X AND THE
6530 " NUMBER OF ELEMENTS IN THE ARRAY J AS INPUT AND CALCULATES
6540 " THE MEAN AND THE STANDARD DEVIATION OF THE ELEMENTS IN THE
6550 " ARRAY
6560
6570 IF(J.GT.1) GO TO 3
6580 AVG=0.
6590 SIGMA=0.
6600 RETURN
6610 3 CONTINUE
6620 DIMENSION X(150)
6630 SUM1=0.
6640 DO 1 N=1,J
6650 1 SUM1=SUM1+X(N)
6660 AVG=SUM1/J
6670 SUM2=0
6680 DO 2 N=1,J
6690 D=X(N)-AVG
6700 2 SUM2=SUM2+D*D
6710 SIGMA=SQRT(SUM2/(J-1))
6720 RETURN
6730 END
6740 SUBROUTINE NUMBER(N1,N2)
6741 " THIS SUBROUTINE CONVERTS EACH TLD NUMBER TO A
6742 " NUMBER BETWEEN 1 AND 150
6743
6750 IF(N1.NE.0) GO TO 11
6760 N2=0
6770 RETURN
6780 11 CONTINUE
6790 CALL OPEN(4,'NUMBER','INPUT')
6800 DIMENSION KEN(150)
6810 READ(4,*) (KEN(L),L=1,150)
6820 CALL CLOSE(4)
6830 DO 1 L2=1,150
6840 IF(N1.EQ.KEN(L2)) GO TO 2
6850 1 CONTINUE
6860 WRITE(6,3)
6870 3 FORMAT(' ','YOU HAVE GIVEN A NON+EXISTANT TLD NUMBER YOU DUM
 DUM')
6880 WRITE(6,4)
```

```
6890 4 FORMAT(' ','NOW I HAVE TO STOP AND YOU HAVE TO START OVER AN
D')
6900 WRITE(6,5)
6910 5 FORMAT(' ','THERE ISNT A THING IN THE WORLD WE CAN DO ABOUT
IT')
6920 WRITE(6,6)
6930 6 FORMAT(' ','DO BE MORE CAREFUL NEXT TIME')
6940 STOP
6950 2 N2=L2
6960 RETURN
6970 END
6980 SUBROUTINE NUMB2(N1,N2)
6990 DIMENSION NUMBER(150)
7000 CALL OPEN(4,'NUMBER','INPUT')
7010 READ(4,*) (NUMBER(L),L=1,150)
7020 CALL CLOSE(4)
7030 N2=NUMBER(N1)
7040 RETURN
7050 END
```

Appendix E. Data Management Program for TLD Environmental Surveillance Measurements

```
20 1 FORMAT(' ','ADD READINGS (1), PRINTOUTS (2)')
30 DIMENSION READ(24,65)
40 DIMENSION X2(150),DOSE(24,65)
50 DIMENSION HOURS(24),CF(150,15)
60 REAL CF2(150),IB(150,15)
70 REAL NUMB(65),NDOSE(24,65),IB2(150)
80 DIMENSION AVGCF(150)
90 DIMENSION AVGIB(150)
100 DATA NUMB/413,411,16,28,47,410,406,403,402,405%
110 ,301,425,426,417,415,401,424,19,300,434,431,427,420,409,430%
120 ,437,613,429,13,24,11,439,14,78,428,418,407,438,408,433,442,7
0,412,414,38,%
130 445,419,443,444,2,423,298,440,628,436,26,435,432,404,441%
140 ,608,416,33,422,421/
150 REAL NDR(24,65)
160 DIMENSION NOS(65),AVGDEV(65),DEV(24,65)
170 REAL NUM(65),MNDR(65,7),SIGMA(65,7)
180 DATA NOS/13,11,56,62,70,10,6,3,2,5,118,25,26,17,15,%
190 1,24,59,117,34,31,27,20,9,30,37,129,29,54,60,52,39,55,84,28,1
8,7,38,8,33,%
200 42,80,12,14,65,45,19,43,44,51,23,115,40,136,36,61,35,32,4,41,
%
210 128,16,63,22,21/
220 READ(5,*) KK
230 IF(KK.EQ.1) WRITE(6,2)
240 2 FORMAT(' ','ENTER MONTH NUMBER')
250 IF(KK.EQ.1) READ(5,*) M
260 DIMENSION L1(7)
270 DATA L1/1,11,21,31,41,51,61/
280 DIMENSION L2(7)
290 DATA L2/10,20,30,40,50,60,65/
300 IF(KK.EQ.1) WRITE(6,4)
310 4 FORMAT(' ','ENTER THE NUMBER OF HOURS THE TLDS WERE IN THE
FIELD')
320 CALL OPEN(1,'HOURS','INPUT')
330 READ(1,*) HOURS
340 CALL CLOSE(1)
350 IF(KK.EQ.2) GO TO 42
360 READ(5,*) HOURS(M)
370 CALL OPEN(1,'HOURS','OUTPUT')
380 WRITE(1,*) HOURS
390 CALL CLOSE(1)
400 42 CONTINUE
410 CALL OPEN(2,'READ','INPUT')
420 READ(2,*) READ
430 CALL CLOSE(2)
440 IF(KK.EQ.2) GO TO 43
450 5 FORMAT(' ','ENTER EACH TLD NUMBER FOLLOWED BY ITS READING,
WHEN DONE TYPE 0,0')
460 385 CONTINUE
```

```
470 READ(5,*) N3,X
480 IF(N3.EQ.0) GO TO 40
490 CALL NUMBER(NUMB,N3)
500 IF(N3.EQ.999) GO TO 385
510 READ(M,N3)=X
520 GO TO 385
530 40 CONTINUE
540 CALL OPEN(2,'READ','OUTPUT')
550 WRITE(2,*) READ
560 CALL CLOSE(2)
570 43 CONTINUE
580 IF(KK.EQ.1) STOP
590 10 CONTINUE
591 DO 18 I=1,24
592 IF(HOURS(I).EQ.0) GOTO 19
593 18 CONTINUE
594 19 I=I-1
600 CALL OPEN(7,'NAM1','INPUT')
610 READ(7,*) ((CF(M1,M2),M2=1,15),M1=1,150)
620 CALL CLOSE(7)
630 DO 26 N=1,65
640 DO 27 JJ=1,15
650 IF(CF(NOS(N),JJ).NE.0.) GO TO 28
660 J=JJ-1
670 GO TO 933
680 28 CF2(JJ)=CF(NOS(N),JJ)
690 J=JJ
700 27 CONTINUE
710 933 CONTINUE
720 CALL STDEV(CF2,J,AVG,SIGMA)
730 AVGCF(N)=AVG
740 26 CONTINUE
750 CALL OPEN(8,'IB','INPUT')
760 READ(8,*) ((IB(M1,M2),M2=1,15),M1=1,150)
770 CALL CLOSE(8)
780 DO 11 N=1,65
790 DO 12 N1=1,15
800 IF(IB(NOS(N),N1).EQ.0.) GO TO 13
810 IB2(N1)=IB(NOS(N),N1)*AVGCF(N)-2.
820 12 CONTINUE
830 13 CONTINUE
840 N1=N1-1
850 11 CALL STDEV(IB2,N1,AVGIB(N),S)
860 DO 6 M=1,24
870 DO6 N=1,65
880 IF(READ(M,N).EQ.0.) GO TO 6
890 DOSE(M,N)=READ(M,N)*AVGCF(N)
900 NDOSE(M,N)=DOSE(M,N)-HOURS(M)*AVGIB(N)*.001
910 NDR(M,N)=1000.*NDOSE(M,N)/HOURS(M)
920 6 CONTINUE
930 DO 22 M=1,I
940 DO 22 L=1,7
950 K1=L1(L)
```

```
960 K2=L2(L)
970 J=0
980 DO 49 I2=K1,K2
990 IF(NDR(M,I2).EQ.0) GO TO 49
1000 J=J+1
1010 X2(J)=NDR(M,I2)
1020 49 CONTINUE
1030 CALL STDEV(X2,J,MNDR(M,L),SIGMA(M,L))
1040 SIGMA(M,L)=SIGMA(M,L)/SQRT(FLOAT(J))
1050 DO 60 I2=K1,K2
1060 IF(NDR(M,I2).NE.0) GO TO 67
1070 DEV(M,I2)=100.
1080 GO TO 60
1090 67 DEV(M,I2)=(MNDR(M,L)-NDR(M,I2))/MNDR(M,L)
1100 DEV(M,I2)=100.*DEV(M,I2)
1110 60 CONTINUE
1120 22 CONTINUE
1130 SUM=0.
1140 DO 62 L=1,7
1150 K1=L1(L)
1160 K2=L2(L)
1170 DO 62 I2=K1,K2
1180 J=0
1190 SUM=0.
1200 DO 61 M=1,I
1210 IF(DEV(M,I2).GT.99.) GO TO 61
1220 J=J+1
1230 SUM=SUM+DEV(M,I2)
1240 61 CONTINUE
1250 IF(SUM.EQ.0) GO TO 62
1260 IF(J.EQ.0) GO TO 62
1270 AVGDEV(I2)=SUM/J
1280 62 CONTINUE
1290 AVG=SUM1/J
1300 SUM2=0.
1310 WRITE(6,111)
1320 111 FORMAT(' ','GENERAL INFORMATION(1) OR SPECIFIC(2)')
1370 15 READ(5,*) K
1380 IF(K.EQ.1) GOTO 16
1390 IF(K.EQ.2) GOTO 17
1400 IF(K.EQ.3) GO TO 64
1410 WRITE(6,14)
1420 14 FORMAT(' ','TYPE 1 OR 2 DUM DUM')
1430 GO TO 15
1440 16 CONTINUE
1450 WRITE(6,20) I
1460 20 FORMAT(' ','THERE ARE',I3,' MONTHS OF DATA IN STORAGE')
1470 DO 220 M=1,I
1480 IF(K.EQ.1) WRITE(6,55) M
1490 55 FORMAT('0','MONTH',I3)
1500 IF(K.EQ.1) WRITE(6,21)
1510 21 FORMAT('-','LOCATION',5X,'NET DOSE RATE',5X,'STDEV')
```

```
1520 DO 220 L=1,7
1530 IF(K.EQ.1) WRITE(6,23) L,MNDR(M,L),SIGMA(M,L)
1540 23 FORMAT(' ',I4,F17.4,F15.3)
1550 220 CONTINUE
1560 IF(K.EQ.1) STOP
1570 17 CONTINUE
1580 WRITE(6,44)
1590 44 FORMAT(' ','ENTER MONTH NUMBER')
1600 READ(5,*) M
1610 DO 520 L=1,7
1620 WRITE(6,53) M,L
1630 53 FORMAT(' '///,' MONTH ',I3,', LOCATION ',I3)
1640 WRITE(6,45)
1650 45 FORMAT('0','TLD',3X,'READING',6X,'CF',6X,'DOSE',6X,'IB',6
X,'NET DOSE RATE')
1660 K1=L1(L)
1670 K2=L2(L)
1680 DO 46 N=K1,K2
1690 N3=NUMB(N)
1700 WRITE(6,47) N3,READ(M,N),AVGCF(N),DOSE(M,N),AVGIB(N),NDR(M,N
)
1710 47 FORMAT(' ',I3,F9.1,F11.3,F8.2,F10.2,F12.3)
1720 46 CONTINUE
1730 WRITE(6,51) MNDR(M,L)
1740 51 FORMAT(' ',//,' MEAN NET DOSE RATE =',F11.4)
1750 WRITE(6,52) SIGMA(M,L)
1760 52 FORMAT(' ',/,' STDANDARD DEVIATION OF THE MEAN =',F11.4)
1770 520 CONTINUE
1780 IF(K.NE.3) STOP
1790 64 CONTINUE
1800 WRITE(6,71)
1810 71 FORMAT(' ',T10,'AVERAGE DEVIATION',/,T10,'   FROM MEAN%
1820 ',/,' TLD',9X,'PERCENT')
1830 DO 66 I=1,65
1840 M=NUMB(I)
1850 WRITE(6,72) M,AVGDEV(I)
1860 72 FORMAT(' ',I3,5X,F10.3)
1862 IF(ABS(AVGDEV(I)).GT.5.2) GO TO 80
1864 IF(ABS(AVGDEV(I)).GT.4.) WRITE(6,81)
1865 81 FORMAT('+',25X,'QUESTIONABLE TLD')
1867 IF(ABS(AVGDEV(I)).LT.0.1) WRITE(6,82)
1868 82 FORMAT('+',25X,'EXCELLENT DOSIMETER')
1870 GO TO 66
1872 80 CONTINUE
1874 IF(ABS(AVGDEV(I)).GT.10.) WRITE(6,83)
1876 83 FORMAT('+',25X,'THROW THIS TLD AWAY')
1878 IF(ABS(AVGDEV(I)).LE.10.) WRITE(6,84)
1880 84 FORMAT('+',25X,'BAD TLD')
1882 66 CONTINUE
1884 STOP
1890 END
```

```
1900 SUBROUTINE STDEV(X,J,AVG,SIGMA)
1910 DIMENSION X(150)
1920 IF(J.GT.1) GO TO 3
1930 SIGMA=0.
1940 RETURN
1950 3 CONTINUE
1960 SUM1=0
1970 DO 1 N=1,J
1980 1 SUM1=SUM1+X(N)
1990 AVG=SUM1/J
2000 SUM2=0
2010 DO 2 N=1,J
2020 D=X(N)-AVG
2030 2 SUM2=SUM2+D*D
2040 SIGMA=SQRT(SUM2/(J-1))
2050 RETURN
2060 END
2070 SUBROUTINE NUMBER(NUMB,N)
2080 REAL NUMB(65)
2090 DO 1 L=1,65
2100 IF(N.EQ.NUMB(L)) GO TO 2
2110 1 CONTINUE
2120 WRITE(6,3)
2130 3 FORMAT(' ','YOU HAVE PUT IN A NON-EXISTENT TLD NUMBER YOU
DUM DUM')
2140 N=999
2150 RETURN
2160 WRITE(6,4)
2170 4 FORMAT(' ','NOW I HAVE TO STOP AND YOU HAVE TO START OVER
AND')
2180 WRITE(6,5)
2190 5 FORMAT(' ','THERE ISNT A THING IN THE WORLD WE CAN DO ABOU
T IT')
2200 WRITE(6,6)
2210 6 FORMAT(' ','DO BE MORE CAREFUL NEXT TIME')
2220 STOP
2230 2 N=L
2240 RETURN
2250 END
```

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(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

An investigation was made of factors affecting the use of commercially-produced CaF_2:Mn thermoluminescent dosimeters for low level environmental radiation monitoring. Calibration factors and self-dosing rates were quantified for 150 thermoluminescent dosimeters. Laboratory studies were made of precision, linear response to dose rate, effects of light, and time-dependent fading. A standard laboratory procedure was devised and a computer program was written to calculate, analyze, and store the large amounts of data that were accumulated. Extensive environmental measurements were subsequently carried out at the Vermont Yankee Nuclear Power Station. The results of this investigation indicate that selected dosimeters, when properly calibrated and corrected for self-irradiation, can be used for accurate and reliable monitoring of low-level environmental radiation.

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