PILOT COMPARISON OF TWO THERMOLUMINESCENT DOSIMETRY SYSTEMS WITH FILM BADGES IN ROUTINE PERSONNEL MONITORING

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Abstract—An intercomparison was made of the performance of two thermoluminescent dosimetry (TLD) systems and conventional film badges in a routine γ-ray personnel monitoring operation. Quartz fiber pocket dosimeters were worn in some cases also but were read out more frequently than the monthly interval used for the other systems.

One of the TLD systems consisted of the U.S. Navy experimental prototype Computer–Indicator CP-748 (XN-1)/PD and Detectors DT-284 (XN-1)/PD (respectively the "reader" and "dosimeters"). The other was a commercial model of foreign manufacture which will be referred to here as the "M" system. Both of these types of dosimeters employed calcium fluoride TLD material sealed in a glass envelope with an internal ohmic heater.

The "M" dosimeters were found to agree with the DT-284's within 10% + 6 mR almost without exception and within 10% + 3 mR in three cases out of four. The quartz-fiber dosimeters agreed with the DT-284's within 10% + 6 mR in three fourths of the cases. 20 mR was regarded as the minimum exposure detectable with the film; in the 31 cases where the film exceeded this minimum, it also exceeded the DT-284 reading by 10% + 25 mR in 18 cases, and by 10% + 50 mR in 8 cases.

Both types of TLD's were found to contain radioactive contamination which gave rise to background readings in excess of ambient background by $\approx$ 21–24 mR/mo.

I. INTRODUCTION

In earlier Naval Research Laboratory Test and Evaluation Reports,[1,2] brief descriptions of the radiation performance of two thermoluminescent dosimetry (TLD) systems were given. The first, a U.S. Navy experimental prototype, consisted of a thermoluminescence reader Computer-Indicator CP-748 (XN-1)/PD and TL dosimeters identified as Detectors DT-284(XN-1)/PD. This system was developed under contract from the Bureau of Ships and was loaned to the Laboratory through the courtesy of Messrs. C. S. Hollander and D. D. Helton, Code 682B of the Bureau of Ships (now NAVELECSYSCOM, Code ELEX 05162). The second TLD system was a foreign commercial one which will be denoted here as the "M" system.

The cited reports[1,2] indicated that the immediate use of either of these systems for routine personnel-monitoring applications at NRL would be somewhat premature, and it was felt that an intercomparison with typical film badges on a pilot basis in monitoring NRL personnel might indicate further strengths and weaknesses not revealed by the other laboratory tests. Hence, some one hundred NRL personnel were asked to wear simultaneously a DT-284 and/or an "M" thermoluminescent dosimeter, in addition to their regular film badge, for four one-month collection periods beginning in February 1965. A part of this group also carried a 0–200 mR quartz-fiber pocket dosimeter for day-to-day routine monitoring.

II. THE DOSIMETRY SYSTEMS

A. *Navy Experimental Prototype System* (*CP*-748 (*XN*-1)/*PD Reader and DT*-284(*XN*-1)/*PD Dosimeters*)

The DT-284 dosimeters (see Fig. 1) use CaF_2: Mn phosphor of the type developed at NRL by Ginther[3] and are normally enclosed in a shield which flattens the response per roentgen over the γ-ray-energy interval from 80 keV to 1.3 MeV; below 80 keV the response rapidly decreases. The reader covers a range of six decades of exposure, full-scale readings being 0.1, 1, 10, 100, 1000 and 10,000 R. The exposure reading is printed out on paper tape along with the serial number of the dosimeter. The group of DT-284 dosimeters tested showed a standard deviation of $\pm 9\%$ in their γ-ray sensitivity distribution; the reading reproducibility of a single dosimeter repeatedly given the same exposure (near full-scale on the 0–10 R range) had a standard deviation of about $\pm 2\%$. The response of the reader vs. Co^{60} γ-ray exposure was strictly linear on each scale, but the high-exposure scales (> 1 R) read lower than they should by as much as 40% because of incorrect densities of the built-in light filters used for range-changing. This had no bearing on the present tests, however, since all exposures encountered were less than 1 R. A more detailed description of this system may be found in ref. 1.

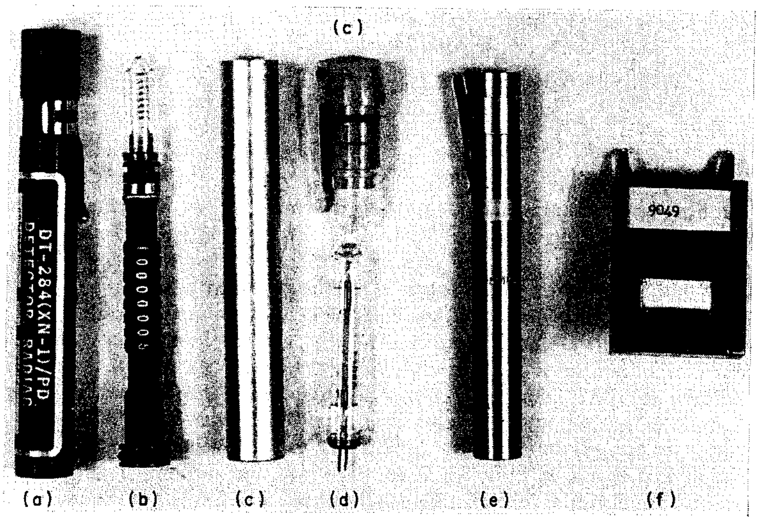

FIG. 1. Principal dosimetry systems involved in the tests: (a) Shielded carrying case for the DT-284 (XN-1)/PD thermoluminescent dosimeter. (b) DT-284 (XN-1)/PD dosimeter. Glass bulb contains CaF_2: Mn phosphor on a Nichrome coil. Numbered cams on attached rod contain identification number information for automatic printout. (c) Carrying case for "M" dosimeter. (d) "M" dosimeter, containing CaF_2:(?) coated on a cylindrical, indirectly heated cathode. (e) 0-200 mR quartz-fiber pocket ion-chamber type dosimeter. (f) NRL film badge.

During the latter part of these tests the Health Physics Staff purchased a commercial TLD reader and a group of dosimeters from the same company that manufactured the Navy prototype, and this commercial system was used in the signal-fading measurements and in some of the radiation background determinations (see Sections IVA and VI). These dosimeters were similar to the DT-284's except for the elimination of the stem bearing the identification cams.

B. *The "M" System*

These dosimeters contain a type of CaF_2 with an unknown activator (not Mn). The reader displays the γ-ray exposure on a meter having full-scale readings of 0.15, 0.5, 1.5, and 5 R. The proper scale (which need not be chosen before the dosimeter is heated in the reader) is selected by push buttons. The sensitivity variation among the individual dosimeters was found to have a standard deviation of about 5%, the reproducibility of readings of a given dosimeter was about 2% S.D., and the response vs. Co^{60} γ-ray exposure was linear within $\pm$ 2% except on the most sensitive scale, where the response was about 15% too low at exposures less than 25 mR. The detectors (see Fig. 1) were enclosed in shields which made the dosimeters' energy response similar to that of the DT-284. A more detailed description of the "M" system will be found elsewhere (e.g. ref. 2).

C. *Film Badge*

The film badge utilized in these tests (see Fig. 1) was the single-filter (1 mm Cd) stainless-steel type developed at Oak Ridge National Laboratory and identified as AEC Catalog No. PF-4B. The badges were fitted with a conventional dosimetry film packet containing high and low sensitivity component films. All the results in this report refer to the more sensitive film. The films were developed at 20°C for 5 min using X-ray developer, rinsed, fixed for 10 min using X-ray fixer, rinsed for 30 min, dried, and their optical densities measured on a densitometer. A calibration set of twenty films (exposure range 10 to 1000 mR) was developed with every film batch, and a calibration curve determined. The film and the quartz-fiber dosimeters were calibrated using the same Co^{60} source. Intercomparison was made of this source with the Co^{60} source used to calibrate the thermoluminescent dosimeters, to assure consistency.

III. TEST SITUATION

The thermoluminescent dosimeters were worn by four groups of employees during these tests. They were: the Reactor Branch of the Radiation Division, the Reactor Materials Branch of the Metallurgy Division, the Dosimetry Branch of the Nuclear Physics Division, and the Health Physics Staff. Physically these groups were located (and the employees primarily worked) in the following NRL buildings: Reactor Branch, 71R; Reactor Materials Branch, 71M; Dosimetry Branch, 5AB, 28A, and 83; Health Physics Staff, 70E. Employees were identified by employee number and building. These four groups of employees were chosen because previous film exposure records indicated that these were the groups most likely to receive detectable radiation exposures. During the first month of the test, February 1965, only an "M" dosimeter plus the film badge and quartz-fiber dosimeter (if issued) were worn by each employee, since the necessary DT-284 dosimeters had not yet arrived from the manufacturer. Both an "M" and a DT-284 dosimeter, in addition to the regular film badge and quartz-fiber dosimeter, were worn during March and April, and only a DT-284 dosimeter plus the film badge and quartz-fiber dosimeter in May. It was originally planned to have a three-month test of the TLD systems plus the film badge and quartz-fiber dosimeter, but the addition of two thermoluminescent dosimeters to the quartz-fiber dosimeter already worn by the Reactor Branch and Reactor Materials Branch employees proved too much strain on shirt pockets (not to mention inconvenience to personnel) and it was decided to omit the "M" dosimeter during the final month of the test.

During the test almost all employees wore their film badges on their belts and the thermoluminescent and quartz-fiber dosimeters in their shirt pockets. This was not ideal, but trying to keep all the devices constantly side by side did not prove practical. It is very unlikely, for the conditions under which the employees worked, that the exposure to the midsection was significantly different from that at the chest. Because of administrative controls on the wearing of personnel-monitoring devices, it is believed that very seldom did any individual wear only a part of his complement of dosimeters. Racks were provided for overnight storage of all dosimeters, except in Building 83, where they were left on employees' desks. A DT-284, an "M" dosimeter, and a film badge were stored

Table 1A. *March Results*

Employee and Bldg. No.	Gross readings (mR)		Correction factors		Corrected readings (mR)		Corrected readings less bkg. (mR)		Quartz-fiber dosimeter readings (mR) (1)	Film badge readings (mR) (2)
	"M"	DT-284	"M"	DT-284	"M"	DT-284	"M"	DT-284		
0000–71R	27	29	0.91	1.05	26	30	3	2	5	—
0181–71R	29	33	1.01	1.20	29	40	6	12	5	—
0338–71R	37	30	0.88	1.14	33	34	10	6	—	—
0760–71R	32	27	0.88	1.09	28	29	5	1	—	—
1049–71R	27	26	0.94	1.27	25	33	2	5	5	—
1181–71R	27	24	0.90	1.13	24	27	1	−1		—
1233–71R	35	35	0.91	1.14	32	40	9	12	5	—
1511–71R	28	(3)	0.90		25		2		—	—
2127–71R	28	25	0.86	1.24	24	31	1	3	—	—
2130–71R	28	32	0.89	1.05	25	34	2	6	10	—
2155–71R	25	29	1.00	1.08	25	31	2	3	—	—
2160–71R	41	34	0.87	1.18	36	40	13	12	—	—
2170–71R	30	30	1.00	1.21	30	36	7	8	15	—
2347–71R	33	26	0.92	1.41	30	37	7	9	5	—
2471–71R	30	32	0.88	1.13	26	36	3	8	—	—
2692–71R	36	(4)	0.90	1.40	32		9		—	—
3405–71R	27	32	0.93	1.02	25	33	2	5	—	—
3413–71R	27	23	0.94	1.32	25	30	2	2	—	—
3509–71R	28	26	1.01	1.20	28	31	5	3	—	—
3581–71R	72	57	0.92	1.08	66	62	43	34	35	—
3606–71R	97	89	0.87	0.93	84	82	61	54	45	50
3673–71R	32	31	0.88	1.03	28	32	5	4	—	—
3808–71R	28	28	0.90	1.11	25	31	2	3	—	25
3941–71R	110 (8)	52		1.08		56		28	30	—
4596–71R	47	37	0.85	1.18	40	44	17	16	15	60
4768–71R	(5)	(5)							5	—
5012–71R	25	26	0.95	1.23	24	32	1	4	—	—
5055–71R	38	34	0.96	1.08	36	37	13	9	—	—
BKG–71R	30	24	0.86	1.28	26	31	3	3		—

For explanation of references (1)–(8) see page 462.

Table 1A (*continued*)

Employee and Bldg. No.	Gross readings (mR) "M"	Gross readings (mR) DT-284	Correction factors "M"	Correction factors DT-284	Corrected readings (mR) "M"	Corrected readings (mR) DT-284	Corrected readings less bkg. (mR) "M"	Corrected readings less bkg. (mR) DT-284	Quartz-fiber dosimeter readings (mR) (1)	Film badge readings (mR) (2)
0138–71M	34	98	0.93	1.21	125	119	102	91	145	50
0484–71M	26	30	1.05	1.13	27	34	4	6	—	—
0890–71M	26	29	0.95	1.16	25	34	2	6	—	—
1067–71M	(5)	(5)							—	—
1117–71M	33	30	0.94	1.17	31	35	8	7	5	—
1405–71M	112	79	0.88	1.25	99	99	76	71	65	40
1429–71M	27	23	0.89	0.98	24	23	1	−5	15	—
1619–71M	52	42	0.93	1.21	48	51	25	23	30	—
1787–71M	28	28	0.96	1.23	27	34	4	6	20	—
2290–71M	26	29	0.88	1.13	23	33	0	5	—	—
2688–71M	28	29	0.85	1.12	24	32	1	4	—	—
3368–71M	44	37	0.91	1.13	40	42	17	14	10	—
3439–71M	33	62 (6)	0.85		28		5		—	—
3655–71M	28	25	0.86	1.22	24	31	1	3		—
3875–71M	33	31	0.80	0.97	26	30	3	2	—	—
4237–71M	28	28	0.94	1.15	26	32	3	4	—	—
4309–71M	27	25	0.88	1.23	24	31	1	3		—
5125–71M	(5)	(5)								—
BKG–71M	27	25	0.84	1.20	23	30	0	2		—
0114–70E	27	26	0.96	1.13	26	30	3	2		—
0117–70E	34	34	0.91	1.03	31	35	8	7		—
0136–70E	25	(3)	0.89		22		−1		30	—
0172–70E	52	47	0.93	1.11	48	52	25	24		—
0495–70E	71	62	0.85	1.14	60	71	37	43		—
0616–70E	25	(3)	0.83		21		−2			—
0777–70E	27	(3)	0.83		22		−1			—
0894–70E	31	23	0.83	1.13	26	26	3	−2		—
0949–70E	63	(7)	0.90		57		34			—
1330–70E	24	(3)	0.95		24		1			—

Table 1A (*continued*)

Employee and Bldg. No.	Gross readings (mR)		Correction factors		Corrected readings (mR)		Corrected readings less bkg. (mR)		Quartz-fiber dosimeter readings (mR) (1)	Film badge readings (mR) (2)
	"M"	DT-284	"M"	DT-284	"M"	DT-284	"M"	DT-284		
2314–70E	27	25	0.92	1.13	25	28	2	0		—
2527–70E	(5)	(5)								—
3046–71E	33	33	0.81	1.13	27	37	4	9		—
3189–70E	24	(3)	0.93		22		−1			—
3239–70E	(5)	(5)								—
4010–70E	32	31	0.88	1.08	28	33	5	5		—
4631–70E	33	29	0.87	1.07	29	31	6	3		—
BKG–70E	25	25	0.90	1.13	23	28	0	0		—
0893–5AB	28	23	0.91	1.20	25	28	1	−1		—
3873–5AB	27	31	0.92	0.99	25	31	1	3		—
BKG–5AB	28	23	0.93	1.27	26	29	2	1		—
2633–28A	27	23	0.90	1.25	24	29	0	0		—
3637–28A	28	30 (6)	0.92		26		2			—
BKG–28A	29	26	0.89	1.14	26	30	2	2		—
0359–83	32	34	0.93	1.01	30	34	6	5		40
2738–83	27	26	0.89	1.07	24	28	0	−1		—
BKG–83	32	28	0.91	0.98	29	28	5	−1		—

1. Quartz-fiber dosimeter readings are corrected for background and insulation leakage. Dash indicates no detectable reading (> 5 mR); blank indicates none issued.
2. Film badge readings are less background in Building 70E. Dash indicates no detectable reading (> 20 mR).
3. Dosimeter not issued.
4. Broken dosimeter.
5. Dosimeter not read.
6. Apparent malfunction of reader.
7. Dosimeter dropped during readout.
8. Dosimeter worn two months.

Table 1B. *April Results*

Employee and Bldg. No.	Gross readings (mR)		Correction factors		Corrected readings (mR)		Corrected readings less bkg. (mR)		Quartz-fiber dosimeter readings (mR) (1)	Film badge readings (mR) (2)
	"M"	DT-284	"M"	DT-284	"M"	DT-284	"M"	DT-284		
0000–71R	26	26	0.91	1.05	24	27	3	1	5	20
0181–71R	32	33	1.01	1.20	32	40	11	14	15	35
0338–71R	32	30	0.88	1.14	28	34	7	8	10	—
0760–71R	38	33	0.88	1.09	33	36	12	10	—	75
1049–71R	26	24	0.94	1.27	24	30	3	4	—	25
1181–71R	(3)	(3)								—
1233–71R	33	31	0.91	1.14	30	35	9	9	—	100
1511–71R	27	(4)	0.90		24		3		—	—
2127–71R	28	21	0.86	1.24	24	26	3	0	—	100
2130–71R	27	27	0.89	1.05	24	28	3	2	—	50
2155–71R	23	27	1.00	1.08	23	29	2	3	5	20
2160–71R	40	31	0.87	1.18	35	36	14	10	25	50
2170–71R	59	51	1.00	1.21	59	62	38	36	60	50
2347–71R	28	24	0.92	1.41	26	34	5	8	10	60
2471–71R	28	26	0.88	1.13	25	29	4	3	10	20
2692–71R	28	22	0.90	1.40	25	31	4	5	—	25
3405–71R	26	30	0.93	1.02	24	31	3	5	5	50
3413–71R	26	22	0.94	1.32	24	29	3	3	—	25
3509–71R	31	25	1.01	1.20	31	30	10	4	10	25
3581–71R	68	60	0.92	1.08	63	65	42	39	30	75
3606–71R	71	69	0.87	0.93	62	64	41	38	40	120
3673–71R	32	28	0.88	1.03	28	29	7	3	—	50
3808–71R	26	28	0.90	1.11	23	31	2	5	—	75
3941–71R	51	46	0.91	1.08	46	50	25	24	40	100
4596–71R	37	30	0.85	1.18	31	35	10	9	—	75
4768–71R	77 (5)	64 (5)	1.00	1.29	77	82	56	56	—	35
5012–71R	24	24	0.95	1.23	23	29	2	3	5	20
5055–71R	32	32	0.96	1.08	31	35	10	9	5	60
BKG–71R	28	21	0.86	1.28	24	27	3	1		—

For explanation of references (1)–(8) see page 465.

Table 1B (*continued*)

Employee and Bldg. No.	Gross readings (mR)		Correction factors		Corrected readings (mR)		Corrected readings less bkg. (mR)		Quartz-fiber dosimeter readings (mR) (1)	Film badge readings (mR) (2)
	"M"	DT-284	"M"	DT-284	"M"	DT-284	"M"	DT-284		
0138–71M	76	56	0.93	1.21	71	68	50	42	35	—
0484–71M	24	140	1.05	1.13	25	158	4	132	—	—
0890–71M	23	23	0.95	1.16	22	27	1	1	—	—
1067–71M	87 (6)	50 (5)							20	—
1117–71M	155	70	0.94	1.17	146	82	125	56	60	—
1405–71M	40	29	0.88	1.25	35	36	14	10	15	—
1429–71M	26	(7)	0.89		23		2		—	—
1619–71M	37	31	0.93	1.21	34	37	13	11	30	—
1787–71M	57	47	0.96	1.23	55	58	34	32	45	—
2290–71M	38	41	0.88	1.13	33	46	12	20	25	—
2688–71M	27	22	0.85	1.12	23	25	2	−1	—	—
3368–71M	(3)	(3)							—	—
3439–71M	28	35	0.85	1.07	24	37	3	11	—	—
3655–71M	27	21	0.86	1.22	23	26	2	0		—
3875–71M	28	29	0.80	0.97	22	28	1	2	—	—
4237–71M	23	(7)	0.94	1.15	22		1		—	—
4309–71M	26	21	0.88	1.23	23	26	2	0		—
5125–71M	(3)	(3)								—
BKG–71M	26	23	0.84	1.20	22	28	1	2		—
0114–70E	61	48	0.96	1.13	58	54	37	28		—
0117–70E	27	(3)	0.91		24		3			—
0136–70E	24	(4)	0.89		21		0			—
0172–70E	56	50	0.93	1.11	52	55	31	29	65	75
0495–70E	28	25	0.85	1.14	24	28	3	2		—
0616–70E	26	(4)	0.83		21		0			—
0777–70E	(3)	(4)								—
0894–70E	28	20	0.83	1.13	23	23	2	−3		—
0949–70E	(3)	(3)								—
1330–70E	(3)	(4)								—

Table 1B (*continued*)

Employee and Bldg. No.	Gross readings (mR)		Correction factors		Corrected readings (mR)		Corrected readings less bkg. (mR)		Quartz-fiber dosimeter readings (mR) (1)	Film badge readings (mR) (2)
	"M"	DT-284	"M"	DT-284	"M"	DT-284	"M"	DT-284		
2314–70E	24	22	0.92	1.13	22	25	1	−1		—
2527–70E	55	60	1.00	1.03	55	62	34	36		—
3046–70E	43	37	0.81	1.13	35	42	14	16		—
3189–70E	26	(4)	0.93		24		3			—
3239–70E	(3)	(3)								—
4010–70E	27	21	0.88	1.08	24	23	3	−3		—
4631–70E	(3)	(3)								—
BKG–70E	23	23	0.90	1.13	21	26	0	0		—
0893–5AB	30	31	0.91	1.20	27	37	2	7		—
3873–5AB	27	39	0.92	0.99	25	39	0	9		—
BKG–5AB	27	28	0.93	1.27	25	35	0	5		—
2633–28A	29	26	0.90	1.25	26	32	1	2		—
3637–28A	32	32	0.92	1.12	29	36	4	6		—
BKG–28A	35	30	0.89	1.14	31	34	6	4		—
0359–83	36	38	0.93	1.01	33	38	8	8		—
2738–83	38	41	0.89	1.07	34	44	9	14		—
BKG–83	85	130	0.91	0.98	77	127	52	97		—

1. Quartz-fiber dosimeter readings are corrected for background and insulation leakage. Dash indicates no detectable reading (>5 mR); blank indicates none issued.
2. Film badge readings are less background in Building 70E. Dash indicates no detectable reading (>20 mR).
3. Dosimeter not read.
4. Dosimeter not issued.
5. Dosimeter worn two months.
6. Dosimeter worn three months.
7. Broken dosimeter.

in each building on the dosimeter rack to determine the local background radiation level. The thermoluminescent dosimeters were collected and read on the same night that the film badges were collected, and were returned to the employees the next morning.

IV. INDICATED EXPOSURES

Tables IA and IB show the results of the testing program for March and April, the months during which both the thermoluminescent dosimeters were worn. The numbers shown under "Gross Readings" are the exposures indicated by the thermoluminescence readers. These readings multiplied by the "Correction Factors" give the "Corrected Readings". Included in these factors are corrections for the following:

A. *Fading of the stored thermoluminescence signal.*

Both the DT-284 and "M" dosimeters exhibit some fading of the stored thermoluminescence signal, the effect being greater in the former. This fading is shown graphically in Fig. 2. These data were obtained at NRL* with the exception of two points at 60 hr and 45 days for the "M" dosimeters (shown by "o"s), which were determined by the Belgian Army (private communication). Fading is arbitrarily taken as zero at 6 min after exposure. The fading correction factors used for the monthly thermoluminescent dosimeter readings were 1.02 for the "M" dosimeters and 1.09 for the DT-284 dosimeters.

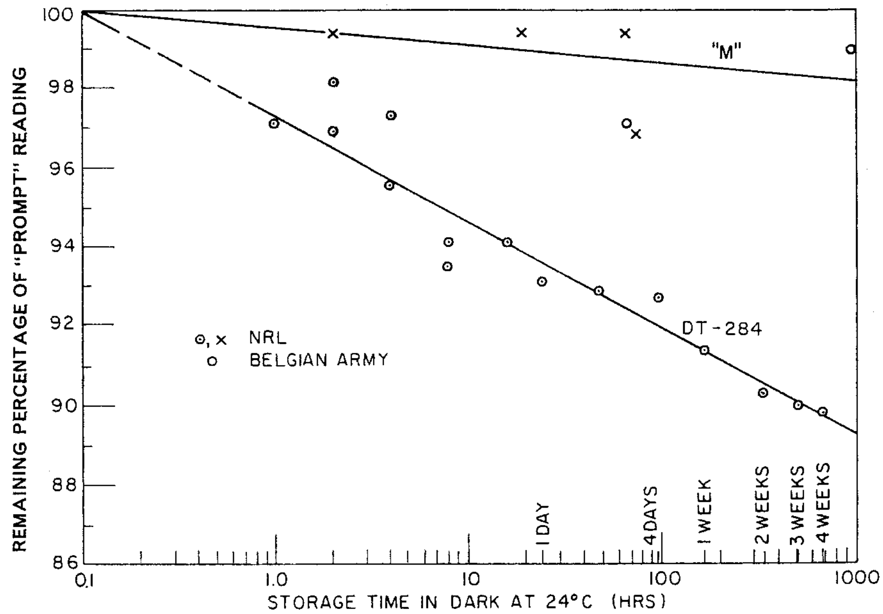

FIG. 2. Percentage of "prompt" (6 min after exposure) reading remaining vs. storage time in dark at 24°C. for thermoluminescent dosimeters. Exposures used for NRL results were 4 R, for the Belgian Army, 60 R.

B. *Difference in Dosimeter Sensitivity*

Each reading was corrected to compensate for the variation in Co^{60} γ-ray sensitivity of each dosimeter from the average of the group.

C. *Reader Calibration Error*

Both the CP-748 and the "M" readers were provided with radioactively-powered light sources

* The authors thank J. A. Pfaff of the NRL Dosimetry Branch for these fading measurements. The commercial TLD system made by the manufacturer of the Navy prototype system was used for these measurements (see Section IIA).

for maintaining constancy of reader sensitivity. In the latter reader the light source was built in. The CP-748 reader was provided with a dummy dosimeter in which the CaF_2: Mn phosphor was caused to radioluminesce continuously by a plating of Ni^{63} on the Nichrome wire filament. When the PM-tube voltage adjustments were set to give the dial readings specified by the manufacturers for the light sources provided, it was found that the thermoluminescence readings obtained with dosimeters of average sensitivity, given known exposures (< 1 R) of Co^{60} γ-rays, were incorrect. Rather than determine a different PM-tube voltage to give correct response, it was decided simply to apply the necessary correction factors: 1.04 for the CP-748 reader, and 0.88 for the "M" reader.

The product of these three component correction factors is the "Correction Factor" in column three of Tables 1A and 1B.

The results given under "Corrected Reading Less Background" are the "Corrected Readings" minus the background readings measured in Building 70E by "M" and DT-284 dosimeters. This building, a wooden structure, has the lowest radiation background of any NRL building, amounting to about 3 mR/month. The "M" and the DT-284 dosimeters read respectively about 21 and 24 mR more than this due to the presence of radioactive contamination in the dosimeter structure, a problem discussed further in Section VI.

The last two columns in Tables 1A and 1B give the quartz-fiber dosimeter readings and the film badge readings, each corrected for Building 70E background (including quartz-fiber dosimeter insulator leakage). The quartz-fiber dosimeter readings were supplied by the Survey and Evaluation Section of the Health Physics Staff, and the film-badge results were taken from the monthly computerized film-badge report prepared by the Health Physics Staff.

V. COMPARISON OF EXPOSURE READINGS

An examination of Tables 1A and 1B shows that very few significantly large exposures were received, most exposures being under 10 mR, as recorded by the TLD systems. Also it is apparent that there is relatively good agreement between the two TLD systems, and with the quartz-fiber dosimeters, but that the film-badge readings are seldom in good agreement with the other dosimeters. The "M" dosimeters agreed with the DT-284's within 10% + 6 mR almost without exception, and within 10% + 3 mR in three cases out of four. The quartz-fiber dosimeters agreed with the DT-284's within 10% + 6 mR in three-quarters of the cases. 20 mR was regarded as the minimum meaningful film reading: below that the reading was assumed to be zero. In the 31 cases where the film read $\geq$ 20 mR, it exceeded the DT-284 reading by 10% + 25 mR in 18 cases, and by 10% + 50 mR in 8 cases.

These observations are shown more clearly in Tables 2 and 3, and in Figs. 3 and 4. Table 2 summarizes all exposures where either TLD indicated an exposure of 10 mR or greater; Table 3 includes only cases where film readings were $\geq$ 20 mR. Figure 3 contains a resumé of the data given in Tables 2 and 3, plotted against the DT-284 reading on the abscissa. The histogram in Fig. 4 illustrates how closely the two TLD systems agreed, even in those instances when either dosimeter gave a net reading of $\leq$ 5 mR.

The closeness of agreement between the thermoluminescent dosimeters and the quartz-fiber dosimeters is to some extent fortuitous, considering the very low exposures and the approximate form in which the quartz-fiber dosimeter readings were recorded. It had not been intended originally to include them in this pilot study; therefore no special arrangements were made to optimize the precision of their readings. Normally the function of these dosimeters at NRL is to provide short-term control of exposures between film-badge readings. Twice a week the technician recorded the exposure (corrected for background and insulator leakage) accumulated since the previous reading, rounding the result to the nearest 5 mR. The readings given in the present tables are the sums of the readings so recorded during each month. It is conceivable, although unlikely, that rounding errors could add up to as much as 20 mR/month by this method.

Two of the rows of data given in Table 2 (indicated by arrows; employees No. 0484 and 0117 in Bldg. 71M, Table 1B) are in poorer agreement than the rest. These two employees kept their dosimeters side-by-side in the

Table 2. Summary of the Larger Exposure Readings in Tables 1A *and* 1B *(corrected reading less background ≥ 10 mR on either TLD)*

"M"	DT-284	Q.F. dosimeter	Film badge
6	12	5	—
10	6	—	—
9	12	5	—
13	12	—	—
43	34	35	—
61	54	45	50
17	16	15	60
13	9	—	—
102	91	145	50
76	71	65	40
25	23	30	—
17	14	10	—
25	24		—
37	43	—	—
11	14	15	35
12	10	—	75
14	10	25	50
38	36	60	50
10	4	10	25
42	39	30	75
41	38	40	120
25	24	40	100
10	9	—	75
10	9	5	60
50	42	35	—
→ 4	132	—	—
→125	56	60	—
14	10	15	—
13	11	30	—
34	32	45	—
12	20	25	—
37	28		—
31	29	65	75
34	36		—
14	16		—
9	14		—

Table 3. Summary of Corrected Readings less Background in Tables 1A *and* 1B *for all Detectable Film Badge Readings*

Film badge	"M"	DT-284	Q.F. dosimeter
50	61	54	45
25	2	3	—
60	17	16	15
50	102	91	145
40	76	71	65
40	6	5	
20	3	1	5
35	11	14	15
75	12	10	—
25	3	4	—
100	9	9	—
100	3	0	—
50	3	2	—
20	2	3	5
50	14	10	25
50	38	36	60
60	5	8	10
20	4	3	10
25	4	5	—
50	3	5	5
25	3	3	—
25	10	4	10
75	42	39	30
120	41	38	40
50	7	3	—
75	2	5	—
100	25	24	40
75	10	9	—
20	2	3	5
60	10	9	5
75	31	29	65

dosimeter rack, and it seems possible that they accidentally exchanged "M" dosimeters. However in that case the 4 mR reading of the "M" dosimeter seems to be much too low.

Although the film-badge readings are not closely correlated with the TLD readings, the film badges did indicate some exposure in every case where either of the TLD systems indicated an exposure in excess of 50 mR. As noted before, the film badge readings generally were higher than the TLD readings in those cases where the film indicated ≥ 20 mR. This becomes very apparent on examination of Table 3; in a number of cases the film badge alone seems to be indicating significantly large exposures which were not detected by any of the other systems, and presumably therefore did not exist. Most of the film badge exposures occurring where the TLD systems showed no exposure were obtained in the NRL Reactor building during a period when a failure of the air con-

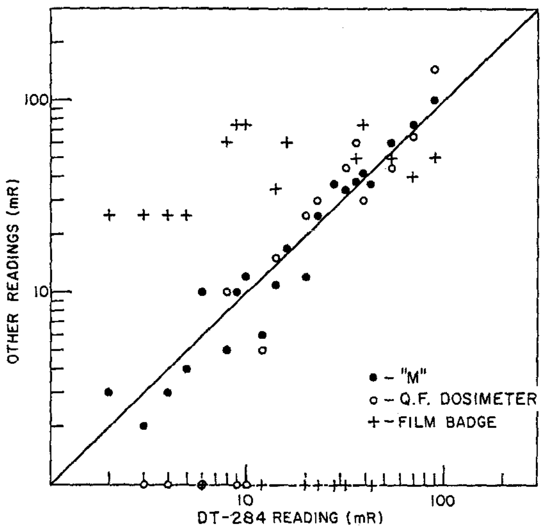

FIG. 3. Resumé of the data in Tables 2 and 3, plotted vs. the DT-284 readings. To avoid crowdings of points, only the first occurrence of each integral value of DT-284 readings is plotted.

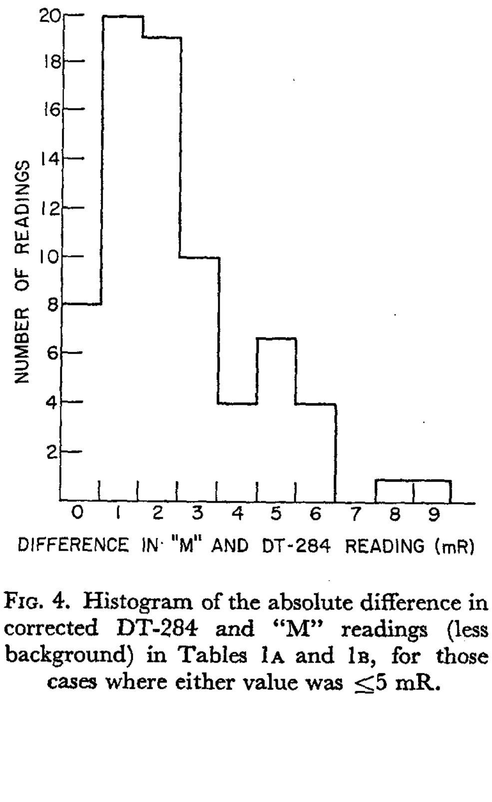

FIG. 4. Histogram of the absolute difference in corrected DT-284 and "M" readings (less background) in Tables 1A and 1B, for those cases where either value was $\leq$5 mR.

ditioning system caused temperatures to rise to 27–32°C, accompanied by high relative humidities. Clearly the film badges were at a disadvantage in these tests because of the adverse environmental conditions, which had no effect on the sealed-glass-bulb type thermoluminescent dosimeters. Better agreement with the TLD results might be expected under more moderate conditions of temperature and humidity, or by using hermetically-sealed film packs. Nevertheless, these tests reveal the extent of the errors which can occur with ordinary film badges in unfavorable environments.

VI. BUILT-IN RADIOACTIVITY OF DOSIMETERS

As can be noted in Tables 1A and 1B, background readings of the TLDs are on the order of 22–25 mR per month. This is primarily due to radioactive materials unintentionally built into the dosimeters. In an effort to determine the amount of this built-in background, dosimeters were stored in a low-background room at the Naval Medical Research Institute, Bethesda, Maryland. The background in this shielded room is negligible compared to ambient background. Dosimeters were stored singly and in groups of five for 135 days (6/18/65 –11/1/65) and read out promptly thereafter. The results of this test are shown in Table 4. All readings have been corrected for variations in individual γ-ray sensitivity of the dosimeters, reader error, and fading. Fading correction factors of 1.02 and 1.12 respectively were used for the "M" and DT-284 dosimeters. The results thus obtained for built-in background exposure agree with others previously determined in the low-background room for a one-month storage period, where fading correction factors of 1.02 and 1.09, respectively, were used. Note that the "M" dosimeters showed the lowest internal-source reading (21 mR/mo) followed by the DT-284 (24 mR/mo) and the commercial equivalent of the DT-284 (27 mR/mo).

In an attempt to identify the radioactive materials in the dosimeters, several dosimeters were taken apart and the glass and phosphor from a single dosimeter granulated and counted separately on a Geiger-Müller and a windowless gas-flow counter. The results of this test are

Table 4. Readings of Dosimeters Stored in Low-Background Room for 137 Days (6/18/65-11/1/65)

Type	Dosimeter number	Corrected reading	Exposure rate
		(mR)	(mR/mo)
"M"	7612 (Single)	87	19
	7605	100	22
	7607	91	20
	7602	94	21
	7624	95	21
	Average	93	21
DT-284	(Single not read)		
	A40	103	23
	A43	105	23
	A24	111	24
	A12	110	24
	Average	107	24
Commercial (Similar to DT-284)	B815 (Single)	131	29
	576	125	27
	A711	125	27
	C43	125	27
	B637	125	27
	Average	126	27

shown in Table 5; they indicate that both the DT-284 phosphor (+ binder) and glass are definitely contaminated. The binder used to hold the CaF_2: Mn on the filament in the DT-284 is potassium silicate; thus the K^{40} is probably responsible for the contamination in that case. The similar commercial model dosimeter is slightly more contaminated than the DT-284, in agreement with the low-background-room readings. The "M" phosphor (+ binder) shows only slight if any contamination, but the glass envelope indicates almost twice as much beta contamination as does the DT-284 glass.

The nuisance of having a relatively large background due to built-in contamination is alleviated somewhat, at least in the case of the DT-284 dosimeters*, by the fact that they respond individually to this contamination approximately in proportion to their response to external γ-radiation. Consequently the built-in background reading accumulated per unit time need not be determined for individual dosimeters. This was demonstrated by comparing the readings obtained after storing 50 DT-284 dosimeters for three months, with those resulting from an 80-mR γ-ray exposure. Figure 5 shows the results of this test. The distribution of the dosimeters' background readings (unshaded histogram) shows a standard deviation of 9.6% which is in agreement with the standard deviation (9.4%) of the 80-mR external γ-ray exposure readings. When the background readings were individually divided by the corresponding external radiation readings, the resulting distribution was reduced to 4.3% S.D. (see shaded histogram, Fig. 5). The readings of an individual dosimeter repeatedly exposed to

* The "M" dosimeters were not given this test because of termination of the loan period of that system.

Table 5. Built-in Radioactivity of Thermoluminescent Dosimeters

Sample	Net count rate (c.p.m.)	
	Geiger counter	Gas flow counter
DT-284 Phosphor + Binder	0.4 ± 0.5	3.3 ± 1
Commercial Model Phosphor + Binder (similar to DT-284)	1.2 ± 0.5	4.3 ± 1
"M" Phosphor + Binder	0.0 ± 0.5	1.3 ± 1
DT-284 Glass Envelope	1.8 ± 0.5	16 ± 2
Commercial Glass Envelope (similar to DT-284)	2.5 ± 0.5	17 ± 2
"M" Glass Envelope	2.8 ± 0.5	31 ± 2

80 mR of γ-rays show a standard deviation of 2.8%, which would probably be the same for repeated background exposures to 80 mR, if such a measurement were feasible. The theory of propagation of errors predicts a distribution with a standard deviation of 4.0% for the ratio of background to γ-ray readings, in good agreement with the 4.3% value obtained. This verifies that the individual DT-284 dosimeters give readings due to built-in radioactivity which are nearly proportional to their γ-ray sensitivities.

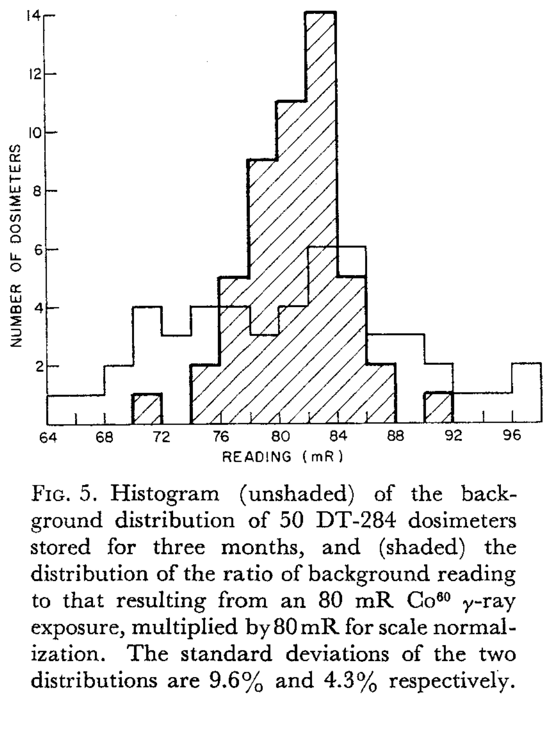

FIG. 5. Histogram (unshaded) of the background distribution of 50 DT-284 dosimeters stored for three months, and (shaded) the distribution of the ratio of background reading to that resulting from an 80 mR Co^{60} γ-ray exposure, multiplied by 80 mR for scale normalization. The standard deviations of the two distributions are 9.6% and 4.3% respectively.

Thus, for purposes of data processing, the built-in background can be treated the same as if it were natural ambient background.

VII. MECHANICAL OPERATION OF THE TLD SYSTEMS

What has been said about the two systems previously (1, 2) was in general confirmed during this test. The "M" system functioned without mechanical failure except for a broken clip on one dosimeter. No "M" dosimeters were broken during the test, and it was possible to obtain a reading for every dosimeter. Difficulty in opening the dosimeters was the most bothersome aspect of the "M" system. There was no detectable change in the response of the "M" dosimeters for the duration of the experiment.

Three DT-284 dosimeters could not be read because of broken bulbs, and two readings were questionable because of apparent malfunction of the reader. In addition, two dosimeter cases were broken by the wearers, and one had to be destroyed in order to remove the jammed detector. At the end of the test, several dosimeters showed apparent flaking of the phosphor from the heating coil, but not enough to cause a detectable change in calibration.

VIII. CONCLUSIONS

The fact that the two independent thermoluminescent dosimetry systems (when properly corrected) agreed so closely with one another, and generally with the quartz-fiber dosimeter results as well, seems to indicate that they were measuring the true exposures with greater accuracy than were the film badges. The latter were operating under the considerable handicap that they were not hermetically sealed against a warm, high-humidity environment, but conditions approaching this are not atypical of Washington in the summer months.

Further comparative testing is underway with the commercial model (made by the manufacturer of the DT-284 and CP-748 system) which is more reliable mechanically inasmuch as it does not contain the auto-identification feature, and uses electronic rather than mechanical range-changing. The results of these tests will be reported later.

The problem of built-in radioactivity in the thermoluminescent dosimeters, which is probably the limitation on minimum detectable exposure at present, can certainly be eliminated in later models. For example, hot-pressed pellets of CaF_2: Mn containing no binder have recently been developed and are now commercially available. The use of one of these in place of the present coil-type element, properly mounted in a non-radioactive glass envelope, should eliminate both the built-in background and the phosphor-chipping problem. Extruded rods and hot-pressed wafers of LiF (TLD-100) have also recently become available, so that the advantage of having the phosphor in a bulk, solid form will not be limited to CaF_2: Mn.

In conclusion one can say that although the thermoluminescent dosimeters used in the present tests out-performed the film badges, it nevertheless seems premature to replace the film badges for NRL personnel monitoring at this time. Current developments in the packaging of thermoluminescent phosphors indicate that considerable additional improvements in their performance may be expected in the immediate future. Moreover some composite dosimeter, perhaps incorporating both high and low-Z phosphors, may be necessary to retain the capability of estimating the γ-ray effective energy,[4] especially for monitoring at an establishment like NRL, which has such a wide variety of radiation sources. Alternatively a single thermoluminescent dosimeter, designed to have a response vs. energy which is proportional to the absorbed dose in specific critical organs, might suffice in some cases.[5]

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