Evaluation of the Neutron Dose Received by Personnel at the LLNL

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This report was prepared to document the techniques being used to evaluate the neutron exposures received by personnel at the LLNL. Two types of evaluations are discussed covering the use of the routine personnel dosimeter and of the albedo neutron dosimeter. Included in the report are f ›ld survey results which were used to determine the calibration factors being applied to the dosimeter readings. Calibration procedures are discussed and recommendations are made on calibration and evaluation procedures.

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Introduction

When it is known that a person may receive significant neutron exposures at LLNL, an albedo neutron dosimeter is assigned to that person. Occasionally a person not wearing an albedo will receive some neutron exposure. Usually this occurs when there has been a recent change in job assignment to a job which involves neutron exposure, or to persons who occasionally receive small exposures or exposure occurring from a one-time job.

Evaluations of Neutron Exposure Using the Personnel Dosimeter Badges

The personnel badges contain two ^{7}Li TLDs and one of either ^{6}Li or natural Li. One of the ^{7}Li TLDs is shielded by 1/16 in. plastic and the security badge to measure the gamma dose and the other is unshielded. The differences between their readings is used to obtain the beta dose. The ^{6}Li or natural Li TLD has a response to thermal neutrons and, when the person is exposed to neutrons, the reading of this TLD will be higher than the reading of the shielded ^{7}Li TLD. Unfortunately, the increased reading of the TLD is not proportional to the neutron dose since it is primarily measuring only the thermal neutron component of the dose. (The fast neutron response of the TLD is very small, even when located on a person.)

To evaluate the person's neutron exposure, the thermal neutron component of the dose must be determined and a calibration factor applied to the TLD reading. The thermal neutron component of the dose is determined at LLNL by using two readings obtained with an Eberline PNR-4 neutron survey instrument.

One measurement is made with the probe in the 9-in. diameter sphere to obtain the total neutron dose rate. A second reading is obtained by removing the probe from the sphere and placing the probe at the same location that the 9-in. sphere measurement was made. The probe is a BF_3 tube which is sensitivie to thermal neutrons. It is 5/8 in. diameter and has an active volume of 1" length beginning 1/2" from the end of the tube. Usually a scaler will be used for these measurements but is not required if the dose rate is high. When the bare probe is exposed to thermal neutrons, the PNR-4 instrument reading is high by a factor of ∿80. The reading with the bare probe is divided by 80 and the adjusted reading is the thermal neutron dose rate. To find the "% thermal" (percent of the total neutron dose that is delivered by thermal neutrons) divide the thermal neutron dose rate by the total neutron dose rate.

The percent thermal value and Figure 1 in the report published in Health Physics[1] (copy attached) is used to determine a calibration factor for the natural Li TLDs. ^{6}Li TLDs are being phased into service to replace the natural Li TLDs. They have higher sensitivity to thermal neutrons by ∿2.1. The curve in Figure 2 is based on Figure 1 and was drawn to correct for the higher response of the ^{6}Li TLD and is used to evaluate the badges where ^{6}Li TLDs were used. The neutron reading of the TLD badge (excess reading of the natural Li or ^{6}Li TLD over the shielded ^{7}Li TLD) is divided by the calibration factor. Care must be taken to use the calibration factor appropriate for the type of tLD in the badge until all the natural Li TLDs have been taken out of service. Then only Figure 2 will be used.

The calibration factor can change dramatically as shown in these figures and it is necessary that field determinations of the percent thermal be made or known from previous work. If the percent thermal is not measured at the time of the exposure, it is sometimes possible to use the results obtained previously from a similar exposure condition to obtain an appropriate calibration factor. Appendix A of this report contains a compilation of survey results obtained at several of our facilities.

To evaluate a dosimeter badge reading it is necessary for the health physicist to know what the source of neutrons was and where the exposure occurred. Since this is normally not known by the health physicist, he must ask the exposed person what the exposure conditions were when he was exposed. The health physicist must then either measure the precent thermal, which is the preferred method, or he can use the appendix to find a similar, appropriate exposure condition.

The calibration of the badges will be performed by the dosimetry group (See Appendix C) and consist of ^{137}Cs gamma ray exposures to the various types of TLDs. *No neutron exposures are made for* calibration purposes, but can be made for quality assurance purposes.

This technique of neutron dose evaluation is not as accurate as the albedo neutron dosimeter because the thermal neutron component of the dose varies rapidly with distance and is subject to large changes caused by neutron moderators or reflectors in the area around the source. If the exposures are to be repeated or routine, an albedo neutron dosimeter should be assigned. If the albedo results and the personnel TLD results disagree, the albedo results are usually the more accurate and should be used.

Evaluation of the Albedo Neutron Dosimeter

Personnel who routinely receive neutron exposures at LLNL will normally be assigned an albedo neutron dosimeter if the dose is expected to be ~10 mrem or larger. Albedos can also be assigned on a short-term basis to cover a one-time exposure situation arising from unusual work or job assignments.

The albedo dosimeters used at LLNL contain two ^{6}Li and two ^{7}Li TLDs and are attached to the personnel badge along with an accident dosimeter (NAD). The badges are all changed on a monthly cycle. The albedo dosimeter we use has cadmium on both sides of the badge and can be worn backwards on the person without affecting its readings. Because it has cadmium completely surrounding the TLDs it is responding primarily to intermediate energy albedo neutrons. The thermal neutron leakage through the cadmium is small but is equal to the albedo response of the badge to ~1 MeV energy neutrons and therefore the albedo can also be used in thermal neutron fields. All albedo neutron dosimeters are very energy dependent and it is necessary that the exposure conditions be known to properly evaluate the dosimeter badge readings.

Fortunately, in a given facility the calibration factors for the albedo dosimeters have been shown to vary within reasonable limits so that in most of our LLNL buildings where neutron exposures occur, a single calibration factor can be used to evaluate exposures occurring in that building. A memo (Appendix B) describing these factors was prepared in February 1978 and is attached to this report. The values given in the memo are still valid. Also, in Appendix A of this report the 9/3 ratios obtained in numerous other surveys are given.

The 9/3-ratio technique is used in the field to determine the calibration factor to apply to the albedo neutron dosimeter. The 9-in. sphere has a response which follows the dose equivalent curve for most energy neutrons fairly close, therefore the response of the 9-in. sphere is used as the total neutron dose rate. The 3-in. sphere has a response reasonably close to that of an albedo neutron dosimeter being worn by a person. The ratio of the 9/3-in. spheres then tells the relative response of an albedo dosimeter compared to the total neutron dose.

The 9/3 ratio is used to determine the calibration factor by making a 9-in. sphere reading followed by a 3-in. sphere reading at the same location. The ratio of the 9/3 in. spheres is determined, and by using the curve given in Figure 3 of Appendix B the calibration factor for that location is obtained. Several measurements are made in the area where the exposure will or has occurred and the calibration factors are averaged or weighted (depending on the variation found in 9/3 ratios and dose rates) to obtain a value to use for the individual's exposure.

Appendix B in this report may also be used in lieu of making additional measurements if a similar exposure condition exists. The description of the measurement location are admittedly skimpy but in most cases additional information about a particular location can be obtained by referring to the references, which are my notebooks. The first digit refers to the notebook number and the second is the page number. Frequently, a map of the area has been sketched to show the measurement point within a room.

Assignment of a calibration factor for an individual is normally made at the time a dosimeter is issued to the employee if the appropirate factor is known. If it is not known, a value of 1.0 is assigned. This serves as a signal to the person reviewing the albedo results (presently Curtis Graham) that the calibration factor is not known. He will then ask the Health Physicist for that area to supply a calibration factor for him. The calibration factors assigned to all personnel should be reviewed at least annually to see if it is appropriate for the work he is presently doing.

The Dosimetry Group is responsible for the calibration of the albedo dosimeters (see Appendix C).

Sometimes it is useful to compare the neutron dose evaluated by either the albedo neutron dosimeter or personnel badge to the gamma dose. In Appendix A I have shown the gamma ray dose rate when available. If there is some question about the neutron dose being assigned, the gamma to neutron ratio can frequently be used to varify the accuracy of the neutron dose. This is, of course, subject to errors, the largest being that the badge may have been exposed to more than one source with varying gamma to neutron ratios.

The use of either albedo neutron dosimeters or the personnel dosimeter to obtain neutron doses depends on the appropriate calibration factor being applied. Care must be taken to assure that this factor is as correct as possible.

It is recommended that when measurements are being made with the PNR-4 instrument, data with the bare probe and 3-in. sphere be made even if only one is to be used. Occasionally it has been found that both the bare and 3-in. readings are needed. The time required to make the extra reading is very small compared to the total time involved in obtaining the readings and the possibility of needing the other reading in the future justifies the extra time.

References

1. Hankins, D.E., "Evaluation of the Fast Neutron Dose Equivalent Using the Thermal Neutron Response of LiF TL Material," Health Physics, Vol. 31, pp. 170-173 (1976).

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Evaluation of the Fast Neutron Dose Equivalent Using the Thermal Neutron Response of LiF TL Material

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A MEASUREMENT of the thermal neutron dose usually is not used to infer the fast neutron dose because there can be large variations in the ratio of the doses from the thermal and the fast neutrons. At the Lawrence Livermore Laboratory (LLL), the present TLD badge is not designed to measure the fast neutron dose (Jo71). It does contain, however, a lithium fluoride TLD (normal lithium) which measures the thermal neutron dose. A study was made to determine if the results from the thermal neutron reading could be related to the total neutron dose.

Obviously, if the ratio of the thermal to fast neutron doses can be established, a calibration factor can be applied to the thermal neutron reading to obtain the total neutron dose. A method of determining this ratio was required which would be fast and easy to make under field conditions. Also required would be a study of the variation in the ratio of the thermal and fast neutron doses at each of our facilities. The results would determine if this procedure could be used and if it could, what accuracy we could expect.

We obtained the evaluation of the thermal-to-fast ratio by using the cadmium-loaded 9-in.-sphere PNR-4 neutron remmeter purchased from Eberline Instrument Corporation.* Although not specifically designed for this application, the BF_3 tube of the instrument can be removed and used to measure the thermal neutron dose rate. (When the bare BF_3 probe is exposed to thermal neutrons, the dose rate indicated by the instrument is high by a factor of ~80.) The fact that a single instrument can be used to determine the thermal dose rate and the total neutron dose rate makes field surveys easier and avoids calibration error inherent in the use of two instruments.

Surveys were made of the thermal-to-fast-neutron ratio at several of our facilities, and with neutron sources in our low-scatter facility. We found it convenient to express the results in terms of "% thermal" which is the dose rate of the thermal neutrons divided by the total neutron dose rate. The % thermal was found to vary from ~0.02 to 30%. For example, in our low-scatter facility the % thermal from a Cf source at 1 m was 0.14%, but when the source is moderated by 25 cm of D_2O the % thermal increases to 12.7%. However, at the facilities we surveyed, we found that the % thermal within that facility normally does not vary greatly. This indicated that the thermal dose probably could be used to evaluate a person's total neutron exposure if the proper calibration factor could be applied.

To determine the calibration factor, TLD badges were exposed on phantoms (1-gal polyethylene jugs) at locations where the % thermal varied from 0.02 to 20%. The % thermal and the total neutron dose rate were determined as described earlier. The badges contain a TLD of normal lithium fluoride (TLD 100), one of lithium-7 fluoride (TLD 700), and one of calcium fluoride (TLD 200). (The TLD 200 readings were not used in this study.) The reading of the TLD was converted to dose using the appropriate gamma calibration factor for each type of TLD material. The TLD 700 dose (gamma) was subtracted from the TLD 100 dose (gamma plus neutron) to obtain the "indicated" neutron dose. To determine the neutron calibration factor, the indicated neutron dose was divided by the dose measured by using the PNR-4 instrument reading. The neutron calibration factor was plotted as a function of the % thermal shown in Fig. 1. Although there is considerable spread in the points, the results indicate that if the % thermal for the exposure conditions is known, the reading of the TLDs from thermal neutrons can be used to determine the fast neutron dose, in most cases within ±30%.

To study the problem of orientation, several of the exposures were made with two or three TLD badges located at various positions around the phantom. Some of these results are shown in Fig. 1 as points aligned at a specific % thermal; e.g. the three points aligned at 0.6, 0.7, 1.1 and 12% thermal. A spread in the TLD responses at various positions around the phantom was found to be less than a factor of 2 at all field locations.

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* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

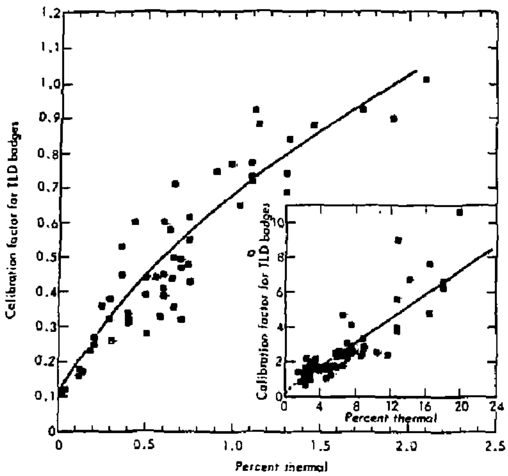

FIG. 1. Curve showing the calibration factor for normal lithium TLDs as a function of the % of the total neutron dose that is delivered by incident thermal neutrons.

The curve shown in Fig. 1 indicates that the reading of the TLDs per unit of dose can vary greatly, depending on the % thermal neutron contribution. For example, at a reactor where the % thermal could be around 19%, the TLD response to neutrons would be high by a factor of 7, but for a PuBe or Cf source at 40–50 cm in air, the % thermal is ~0.1% and the badge would under-respond by a factor of ~5. Obviously, the location where the individual worked must be established if the dose evaluation is to be correct.

The curve shown in Fig. 1 can be used to evaluate the simple TLD badge system supplied by commercial vendors which contains only a TLD of normal lithium. To evaluate the exposure the % thermal would have to be determined and, since the TLD also responds to gamma, the neutron-to-gamma dose ratios are required. If the neutron-to-gamma ratio indicates a higher neutron dose rate than the gamma dose rate and the percent thermal is high, the response of the badge would be primarily to neutrons. For example, assume a % thermal of 19% and a neutron-to-gamma ratio of 2. From Fig. 1 the calibration factor is 7, indicating that the TLD will over-respond to the neutrons by a factor of 7. If the person receives a dose of 300 mrem total (100-mrem gamma and 200-mrem neutron) the TLD reading would be 1500 mrem, 100 mrem for the gamma rays plus 1400 mrem (200 × 7) for the neutron dose. The TLD reading would be high by a factor of 5. An example resulting in a low reading would be a PuBe or ^{252}Cf source where the neutron-to-gamma ratio is about 25. For work at 40–50 cm from the sources the % thermal is ~0.1% and the corresponding calibration factor from Fig. 1 is 0.2, indicating that the TLD will under-respond by a factor of 5 to the neutrons. For a dose of 260 mrem total (10-mrem gamma and 250-mrem neutron) the TLD reading would be 60 mrem, 10 mrem for the gamma rays plus 50 mrem (250 × 0.2) for the neutron dose. The TLD reading would be only 23% of the total dose.

Figure 1 was prepared from results obtained using TLDs of normal lithium. If TLDs enriched in ^6Li is used, the sensitivity increases by a factor of 6–10 (depending on the relative thickness of the TLDs and other factors). This would increase the calibration factors by this amount, but the shape of the curve should remain constant.

In this study, the bare probe of the BF_3 tube was used to determine the thermal neutron dose. Some of the response of the bare probe is to higher energy neutrons which can become significant if the thermal component of the total dose is small. The higher energy neutron response of the instrument is determined by using a Cd sleeve placed over the

BF_3 tube. To keep this procedure as simple as possible, we elected not to use a cadmium sleeve which would have required a third measurement at each point. The results obtained with a Cd sleeve indicate that the effect on the curve shown in Fig. 1 is small and is confined to the part of the curve where the % thermal is less than 0.5%.

Experience in using this procedure to evaluate personnel exposure has in most cases been satisfactory. Extensive surveys have been made in areas where neutron doses are received, and have established what variations exist in the percent thermal. In some cases the variation in the percent thermal is very small, for example, the area around a fissile storage vault, inside the storage vault or outside the shielding of an accelerator. At these locations the evaluation of the person's dose is estimated to be within the ±30% found in the spread of experimental results. At other areas, the variation in % thermal is larger and the evaluation of the dose correspondingly less accurate. The worst situation is at the Radiochemistry Building where spontaneous fission sources are handled unshielded and in gloved boxes shielded with water (1 ft thick). The % thermal from a bare source being handled in this facility is about 0.3–0.5%, and for the same source in the gloved boxes between 4 and 7%. The corresponding calibration factors for the TLD badges are ~0.4 and ~2.0 (see Fig. 1). The error in evaluating a dose received in this facility could be as large as a factor of 5 if the wrong calibration factor were applied. By using personal interviews with the workers, we believe we can estimate their dose to within a factor of 2. In addition, the persons who do most of the material handling are given albedo neutron dosimeters.

While this study was being made of the bare TLD response, we also obtained data to evaluate albedo neutron dosimeters (Ha75). Our conclusions were that the error in evaluation of personnel exposure would be smaller if albedo neutron dosimeters were used. Although albedo neutron dosimeters are very energy-dependent, the variation in the response of the dosimeters is only a factor of 2 for the Radiochemistry facility, compared to the factor of 5 indicated above for the bare TLDs. In some cases albedo neutron dosimeters would give only a small improvement, but in others a potential factor-of-10 error could be reduced to ±40%.

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Jo71 Jones D. E., Petrock K. F., Samardzich B. G. and Shapiro E. G., 1971, Thermoluminescence Dosimeter for Personel Monitoring, Lawerence Livermore Lab. Rept *UCRL-73084*.

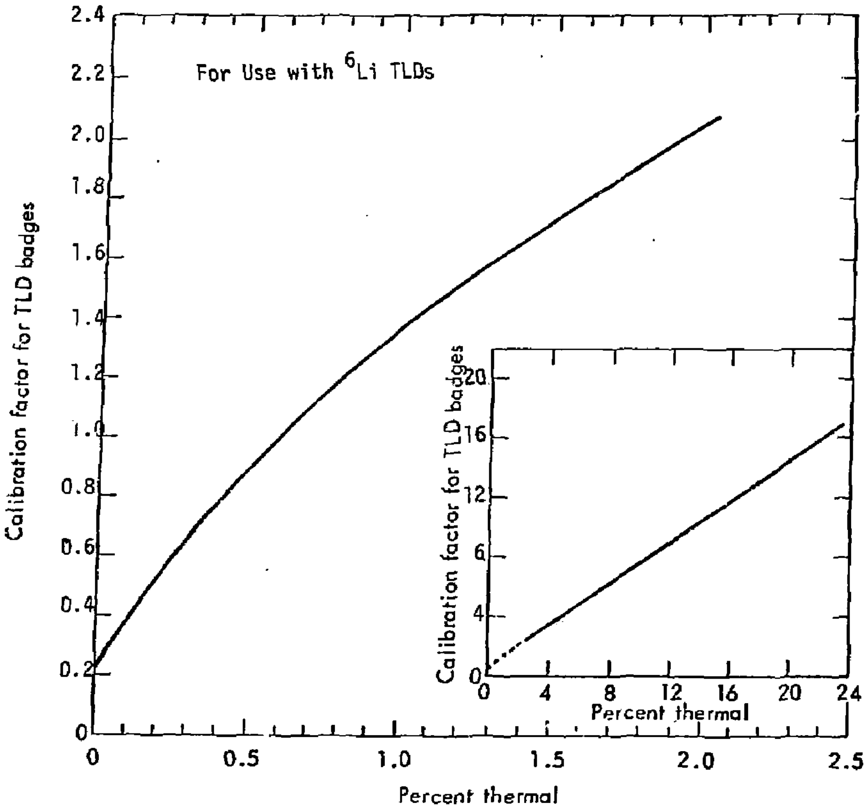

FIG. 2 Curve showing the calibration factor for lithium-6 TLDs as a function of the % of the total neutron dose that is delivered by incident thermal neutrons.

Appendix A Survey Results

BUILDING 251

Reference*	Location	9/3 ratio	% Thermal	dose Rates n	γ
1-11	On table top in room 1301A,	0.29	5.6	0.5	
	Room 1232 in front of Cm box	0.29	9.0	1.5	
	Room 1232 on top corner of Cm box	0.86	1.2	12	
	Shelf in room 1301A	0.28	5.5	1.4	
	On table top in room 1301A	0.25	6.2	0.4	
1-13	Near west wall in room 1248	0.38	7.0	0.1	
1-22	Room 1234	0.35	1.3	9.0	1.2
	Room 1234	0.30	4.7	1.8	0.7
	Room 1234	0.31	5.4	1.1	0.1
	Room 1234	0.37	2.0	4.3	1.0
	Room 1234	0.33	3.1	2.5	0.7
	Room 1234	0.35	1.4	8.6	1.2
1-23	Room 1232	0.29	6.2	1.5	0.7
	Room 1232	0.31	8.8	1.2	1.3
	Room 1232	0.36	7.0	1.5	1.9
	Room 1232	0.33	4.8	1.9	2.4
	Room 1232	0.26	10.8	0.5	0.3
	Room 1232	0.28	7.9	1.4	1.0
	Room 1232	0.38	5.2	1.8	2.4
1-45	Room 1234	0.35	1.3	8.0	
	Room 1234	0.28	4.7	1.7	
	Room 1234	0.26	5.8	1.0	
	Room 1234	0.33	7.4	1.6	
	Room 1232	0.32	5.4	1.9	
	Room 1232	0.34	9.2	1.2	
2-12	In front of Cm box in 1232 source at back	0.52	4.7	2.5	2.0
	In front of Cm box in 1232 source at center	0.60	3.4	4.1	2.0
	In front of Cm box in 1232 at center	0.45	5.0	2.7	1.6
	Room 1035 inside cave	0.35	5.2	1.3	0.8
2-13	Room 1035 next to wall	0.27	6.6	0.9	0.3
	Room 1035 in front of center box	0.33	11	1.4	0.7
	Room 1035 behind box source at front	0.38	2.0	50	2.0
	Room 1035 near source	0.78	1.4	110	
	Source in pig, over top, lid removed	0.94	1.25	300	
	Source in pig, over top, lid removed	1.0	1.25	200	
	In bead blaster	0.83	0.38	100	
	in bead blaster	0.89	0.39	80	
2-14	Source in pig, at side of pig	1.0	2.0	170	
	Source in desk top cave	0.33	5.1	36.3	

*These refer to the author's notebook number and page. For example, 1-11 is book #1, page 11.

BUILDING 251 (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
2-20	Box in 1232, 12 in. from face of box	0.55	4.0	6.4	
2-22	Room 1232 in front of Cm box	0.34	8.2	1.8	
	PuBe source on top of barrel	2.77	0.06	22.2	
2-38	Survey of Cm-Au in pig on table top @ 1 ft	1.02	0.28	7.8	
	Survey of Cm-Au in pig on table top @ 1.5 ft	0.82	0.56	4.0	
	Survey of Cm-Au, no pig on table top @ 1.5 ft	0.80	0.64	3.9	
	Survey of Cm-Au, no pig on table top @ 1 ft	1.04	0.29	8.1	
3-24	Room 1232 next to wall	0.45		5.7	
	Room 1232 corner	0.40		1.4	
3-25	Front of cave room 1232	0.41		0.4	
	Side of cave room 1232	0.48		0.9	
3-26	Room 1117	0.98		8.4	
	Hall outside room 1117	0.73		3.0	
3-27	Room 1234 in SW corner	0.42		3.5	
	Room 1234 in NW corner	0.38		1.4	

BUILDING 255

Reference	Location	reading	9/3 ratio	% Thermal	dose Rates n	γ
1-45	Over neutron cell in 255 calibration area	1559	0.45	3.5	0.5	
	Over neutron cell in 255 calibration area	401	0.45	1.1	5.3	
	Over neutron cell in 255 calibration area	310	0.41	1.2	8.8	
	Over neutron cell in 255 calibration area	200	0.39	1.1	18.9	
	Over neutron cell in 255 calibration area	92	0.41	1.1	52.8	
	Over neutron cell in 255 calibration area	41	0.44	0.94	92.2	
	At door to C Cell		0.30	10	2.8	
1-53	PuBe Bare 1M		2.44	0.12	64.9	
	PuBe Bare 2M		1.47	0.37	20.6	
	Cf Bare 1M		1.78	0.14	2590	
	Cf Bare 2M		1.15	0.45	772	
	PuBe 2 cm Poly 1M		1.64	0.22	55.6	
	PuBe 2 cm Poly 2M		1.14	0.56	18.1	
1-54	Cf 2 cm Poly 1M		1.09	0.29	1962	
	Cf 2 cm Poly 2M		0.81	0.75	634	
	PuBe 5 cm Poly 1M		1.23	0.63	44.1	
	PuBe 5 cm Poly 2M		0.935	1.03	15.0	
	Cf 5 cm Poly 1M		0.76	1.11	1221	
	Cf 5 cm Poly 2M		0.57	1.73	391	
1-55	PuBe 10 cm Poly 1M		1.13	1.13	27.1	
	PuBe 10 cm Poly 2M		0.84	1.64	8.46	
	Cf 10 cm Poly 1M		0.68	2.35	568	
	Cf 10 cm Poly 2M		0.54	3.15	183	
	PuBe 5 cm D_2O 1M		1.13	0.20	53.5	
	PuBe 5 cm D_2O 2M		0.81	0.55	17.4	
1-56	Cf 5 cm D_2O 1M		0.77	0.25	1727	
	Cf 5 cm D_2O 2M		0.58	0.74	563	
	PuBe 10 cm D_2O 1M		0.61	0.43	43.9	
	PuBe 10 cm D_2O 2M		0.55	0.97	14.1	
	Cf 10 cm D_2O 1M		0.38	0.66	1228	
	Cf 10 cm D_2O 2M		0.35	1.45	402	
1-57	PuBe 15 cm D_2O 1M		0.37	1.37	30.3	
	PuBe 15 cm D_2O 2M		0.34	2.14	10.3	
	Cf 15 cm D_2O 1M		0.23	2.34	779	
	Cf 15 cm D_2O 2M		0.22	3.45	270	
	PuBe 25 cm H_2O 1M		1.18	1.31	9.70	
	PuBe 25 cm H_2O 2M		0.86	2.06	3.0	

BUILDING 255 (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
1-58	Cf 25 cm H_2O 1M	0.77	2.78	134	
	Cf 25 cm H_2O 2M	0.59	3.75	45.6	
	PuBe 10 cm H_2O 1M	1.13	1.03	34.6	
	PuBe 10 cm H_2O 2M	0.87	1.59	10.9	
	Cf 10 cm H_2O 1M	0.71	2.03	827	
	Cf 10 cm H_2O 2M	0.55	2.74	260	
1-59	PuBe 25 cm D_2O 1M	0.31	6.4	16.3	
	PuBe 25 cm D_2O 2M	0.29	7.5	5.58	
	Cf 25 cm D_2O 1M	0.18	12.7	344	
	Cf 25 cm D_2O 2M	0.18	14.1	126	
	PuBe 20 cm Al 1M	1.17	0.18	63.2	
	Pu Be 20 cm Al 2M	0.81	0.58	19.3	
1-60	Cf 20 cm Al 1M	0.94	0.20	2216	
	Cf 20 cm Al 2M	0.64	0.66	678	
	PuBe Bare 0.5M	3.11	0.060	213	
	PuBe Bare 3.0M	0.99	0.67	10.4	
2-67	10" out from storage cask in C Cell	0.83	0.53	38.4	
4-95	Cf Bare 50 cm	2.38	0.037		
	Cf Bare 1M	1.96	0.134		
	Cf Bare 2M	1.24	0.42		
4-98	25 cm D_2O @ 1M	0.197	12.7		
	25 cm D_2O @ 2M	0.198	15.2		
4-137	25 cm H_2O @ 1M	0.866			
	25 cm H_2O @ 2M	0.648			
4-138	20 cm Al @ 1M	0.997			
	20 cm Al @ 2M	0.702			
4-139	10 cm Poly @ 1M	0.752			
	10 cm Poly @ 2M	0.596			
5-36	Next to north wall Cf Bare	0.49			
	Next to north wall 25 cm D_2O	0.18			
	Next to north wall 25 cm H_2O	0.34			
	Next to north wall 10 cm D_2O	0.22			
	Next to north wall 20 cm Al	0.32			
	Next to north wall 10 cm Poly	0.33			
	Next to north wall 5 cm Poly	0.34			
	Next to north wall 2 cm Poly	0.41			
	Next to north wall 5 cm D_2O	0.32			
	Next to north wall 15 cm D_2O	0.18			
	Next to north wall PuBe	0.60			

BUILDING 255 (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
5-36	Next to east wall Cf Bare	0.61			
(cont)	Next to east wall 25 cm D_2O	0.17			
	Next to east wall 25 cm H_2O	0.42			
	Next to east wall 10 cm D_2O	0.24			
	Next to east wall 20 cm Al	0.39			
	Next to east wall 10 cm Poly	0.38			
	Next to east wall 5 cm Poly	0.40			
	Next to east wall 2 cm Poly	0.47			
	Next to east wall 5 cm D_2O	0.37			
	Next to east wall 15 cm D_2O	0.17			
	Next to east wall PuBe	0.74			
5-52	Bare Cf @ 1.064M	1.88			
	Bare Cf @ 1.114M	1.83			
	Bare Cf @ 2.064M	1.20			
	Bare Cf @ 2.114M	1.15			
	25 cm H_2O @ 1.064M	0.86			
	25 cm H_2O @ 1.114M	0.85			
	25 cm H_2O @ 2.064M	0.69			
	25 cm H_2O @ 2.114M	0.64			

Teledyne (332)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
4-64	26" center to center 1st unit	0.98	0.28	38.6	10
	26" center to center 2nd unit	1.08	0.28	30.8	18
	8 ft center to center 2nd unit	0.50	1.3	5.6	2.8
	8 ft center to center 1st unit	0.64	1.1	7.7	1.8
	4 ft center to center 1st unit	0.81	0.5	20.3	4
	6 ft center to center 1st unit	0.65	0.78	11.6	2.6
	9 ft center to center 1st unit	0.53	1.3	6.8	1.6
	12 ft center to center 1st unit	0.49	1.7	1.2	1.2
	15 ft center to center 1st unit	0.43	1.9	1.5	1.5
	contact with shield 2nd unit	1.06	0.25	43.6	26
	3 ft from cage 2nd unit	0.63	0.78	10.4	6
	contact 1st unit	1.34	0.11	137	38
	in far corner	0.37	3.4	2.1	0.7
	contact 2nd unit	1.34	0.14	110	60
	work area at desk	0.36	3.4	2.1	0.6
	Outside Poly shield	0.62	2.8	20.6	
5-73	on cart next to shipping container 303	1.31	0.21	47.2	22
	on cart next to shipping container 302	1.11	0.25	34.4	35
	~ 9 ft	0.55	1.4	6.0	
5-74	Contact Fins #302	1.29	0.10	95.0	70
	Contact Fins #303	1.36	0.086	121	45
5-110	Unit 304 28.5" from center	1.08	0.41	55	25
	Unit 304 contact	1.33	0.19	136	60
	Unit 305 28.5" from center	0.97	0.41	41	25
5-111	Unit 305 cotact	1.31	0.13	99	60
	304, behind Poly shield, 48" from source	0.46	3.4	5.8	6.0
	304, behind Poly shield, 48" from source	0.78	0.74	23	8.5
	Far end of room	0.26	4.9	1.2	0.5
	Far end of room	0.40	3.6	0.9	0.5
	Far end of room	0.40	3.8	1.0	0.5
5-136	Room 1337 (in storage behind Poly)	0.52	1.5		3.3
	Room 1337 (in storage behind Poly)	0.52	2.5		3.5
	Room 1337 (in storage behind Poly)	0.48	2.3		4.2

ICT

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
1-18	Snoopy location near fence	0.30	6	0.8	0.25
	Room 196	0.31	9	0.2	0.3
	Step of Bldg. 218	0.22	10	0.1	0
	Corner office in Bldg. 218	0.40	8	0.2	
	Balcony west side of Bldg. 219	0.28	5	0.2	
1-20	Shop Room 162	0.33	8.6	0.2	
	Outside trailer 25	0.24	7.6	0.5	
	Bldg. 219 room 188	0.29	10.3	0.08	
	Bldg. 218 room 203	0.27	8.4	0.2	
	Bldg. 212 room 240	0.45	9.0	0.1	
	At Snoopy location	0.27	6.0	0.8	
1-24	North side @ 8ft	0.30	6.1	2.0	
	North side @ 30 ft	0.27	6.3	0.8	
	North side west of trailer	0.34	4.2	0.6	
	North side across street	0.29	4.4	0.3	
	South side @ 4 ft	0.36	4.0	1.8	
	South side edge of road	0.32	4.2	1.1	
	South side Snoopy location	0.28	4.7	0.9	
	South side across road	0.30	3.4	0.3	
3-19	Next to fence	0.36		0.56	0.25
3-20	South side of Bldg.	0.47		1.9	0.55
	South side of Bldg.	0.41		0.9	0.30
3-21	In front of main door	0.33		0.9	0.25
	At side of main door	0.36		1.9	0.4
3-22	Center of east door	0.39		3.0	0.4
	5 M from wall	0.33		1.1	0.28
3-30	On top of Bldg.	0.57		15	
	On top of Bldg.	0.60		11	
3-31	On top of Bldg.	0.59		33	
	On top of Bldg.	0.62		53	
3-32	On top of end Bldg.	0.46		3.7	
	On top of end Bldg.	0.35	6.7	2.0	

BUILDING 233

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
1-41	Various locations in center of Bldg.	0.46	3.3	1.1	1.5
	Various locations in center of Bldg.	0.35	4.1	0.6	2.5
	Various locations in center of Bldg.	0.63	1.4	2.3	3.5
	Various locations in center of Bldg.	0.30	4.2	0.7	1.5
	Various locations in center of Bldg.	0.49	3.3	1.4	1.5
	Various locations in center of Bldg. near neutron storage	0.53	2.4	3.3	2.5
	Various locations in center of Bldg. near neutron storage	0.58	0.21	5.8	1.5
	Various locations in center of Bldg. near neutron storage	0.50	2.8	1.8	1.3
	Various locations in south end of Bldg.	0.56	2.5	0.5	0.4
	Various locations in south end of Bldg.	0.39	3.5	0.2	0.1
	Various locations in south end of Bldg.	0.53	2.1	1.0	1.8
	Various locations in south end of Bldg.	0.44	4.3	0.1	0.2
1-43	Various locations in south end of Bldg.	0.35	4.6	0.2	1.5
	Various locations in south end of Bldg.	0.42	3.5	0.1	0.2
	Various locations in south end of Bldg.	0.41	5.7	0.1	0.1
	Various locations in south end of Bldg.	0.38	4.6	0.1	0.7
	Various locations in south end of Bldg.	0.47	2.3	0.1	0.1
	Various locations in south end of Bldg.	0.47	3.5	0.06	0.06
	Inside classified storage vault	0.41	3.2	0.3	1.5
	Inside classified storage vault	0.53	1.7	0.6	7.0
	Inside classified storage vault	0.55	1.5	0.6	5.5
	In office area near storage vault	0.37	1.7	0.8	
2-72	Near source storage area	0.71	2.0	8.2	
	Near source storage area	0.58	1.9	6.9	
	Near source storage area	0.54	2.1	3.0	
	Near source storage area	0.63	1.7	8.5	
	Near source storage area	0.84	1.8	9.4	
2-73	Near source storage area	0.43	3.2	3.2	
	Near source storage area	0.84	1.7	9.6	
3-41	Near source storage area	0.49	3.2	2.3	
	Near source storage area	0.86	1.3	11.3	
3-134	Office area	0.40	4.7	0.027	0.045
	Office area	0.30	3.2	0.047	0.47
	Office area	0.20	8.1	0.013	0.056

SITE 300

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
2-44	At gate	0.42	3.0	2.3	4.5
	In control trailer	0.26	4.8	1.6	~0.6
	In film trailer	0.39	4.3	1.8	~4.0
5-1	Survey at 851 ready room	0.16	3.7	2.8	1.5
	Survey at 851 ready room	0.17	3.4	2.8	1.5
	Survey at 851 ready room	0.16	4.7	2.5	1.3
	Survey at 851 ready room	0.18	3.6	2.4	1.0
5-2	Open storage room	0.22	3.1	6.0	2.3
	Room 119	0.36	2.2	6.1	2.2
	Room 119	0.15	6.2	1.4	1.2
5-3	On dock in front of 851	0.23	2.5	6.8	5.3
	On dock in front of 851	0.19	3.4	3.7	1.8
	On dock in front of 851	0.22	3.1	4.1	2.2
5-4	Parking lot	0.43	2.4	5.7	4.5
	Parking lot	0.37	2.5	5.2	3.4
	Road NE	0.46	2.2	6.3	6.5
	Road NE at gate	0.40	2.4	7.5	11
5-5	Road NE at gate	0.29	2.4	4.3	3.4
	Behind 851B	0.21	3.8	2.2	1.8
	Behind 851B	0.14	6.1	0.69	1.2
	Behind 851B	0.11	8.2	0.29	0.15
5-6	Inside 851B	0.15	13.5	0.04	0
	Road SE	0.28	2.5	3.7	1.8
	Road SE	0.28	2.4	0.55	3.4
	Doorway to 851	0.13	7.1	0.49	0.15
5-7	Inside 851 entrance hall	0.22	10.8	0.02	0
	Inside 851 door to 115	0.23	4.3	0.24	0.1
	Inside 851 entrance hall	0.30	10.3	0.37	0
	Room 105 port #7	0.24	1.3	0.90	0.4
5-8	Room 105 port #7	0.23	1.5	0.35	0.4
	Room 105 port #7	0.12	8.5	0.05	0.1
	Room 117	0.20	7.1	0.01	0.1
	Room 117	0.18	7.6	0.01	
	Outside, on dock, near open storage	0.23	2.6	6.9	8
5-9	Outside, on dock, near open storage	0.23	2.6	7.0	
	Outside, on dock, near open storage	0.20	4.8	2.5	0.75
5-10	Outside, on dock, near open storage	0.16	7.8	0.7	0.55

SITE 300 (*continued*)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
5-16	On dock	0.26	2.7	7.9	6.4
	Room 119	0.29	3.2	6.8	
	In ready room	0.21	4.1	4.3	
	Road, at fence	0.24	2.1	8.2	11.5
5-76	Outside, on dock, near open storage 87 MeV	0.25	2.4	7.7	
	Outside, on dock, near open storage 104 MeV	0.24	2.5	9.6	
	Ready room	0.23	2.5	6.0	
	On dock near entrance to 851	0.22	2.7	5.8	

BUILDING 612

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
5-131	Welding of box containing Cm	0.76	0.003	27	
	Welding of box containing Cm	0.75	0.004	9.2	
	Welding of box containing Cm	0.71		12.6	

BUILDING 131

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
3-68	PuBe in source bucket	1.17	1.0	44	5.0
	PuBe in air	3.35	0.03	58	3.0
	Device on stand	1.12	0.44	2.6	3.0
	PuBe in bucket on floor with 4" Borated Poly	1.39	0.21	17	

BUILDING 231 VAULT

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
1-35	Various locations inside vault	0.63	0.6	4.1	7
	Various locations inside vault	0.53	0.7	3.1	4.5
	Various locations inside vault	0.70	0.5	4.2	4.5
	Various locations inside vault	0.59	0.6	3.5	4.0
	Various locations inside vault	0.73	0.4	4.5	4.5
	Various locations inside vault	0.88	0.4	6.0	6
	Various locations inside vault	0.55	0.8	2.8	2.5
1-36	Various locations inside vault	0.60	0.6	3.7	4.0
	Various locations inside vault	0.56	0.6	3.0	4.5
	Various locations inside vault	0.62	0.6	3.1	4.0
	Various locations inside vault	0.59	0.6	3.2	3.0
	Various locations inside vault	0.53	1.0	2.3	2.5
	Various locations inside vault	0.49	0.8	2.1	2.0
	Various locations inside vault	0.46	1.0	1.5	2.5
	Various locations inside vault	0.55	0.9	2.6	2.0
	Various locations inside vault	0.66	0.6	3.8	5.0
	Various locations inside vault	0.60	0.6	3.3	6.0
	Various locations inside vault	0.60	0.6	3.2	5.0
	Various locations inside vault	0.78	0.4	5.0	7.0
	Various locations inside vault	0.41	1.2	1.0	1.5
1-37	Various locations inside vault	0.40	1.4	0.9	1.0
	Various locations inside vault	0.63	0.7	4.2	5
	Various locations inside vault	0.90	0.3	6.5	1.1
	Various locations inside vault	0.69	0.6	4.2	7.5
	Various locations inside vault	0.70	0.4	4.7	6
	Various locations inside vault	0.61	0.6	3.5	4
	Various locations inside vault	0.62	0.6	3.3	35
	Various locations inside vault	0.44	1.1	1.5	
	Various locations inside vault	0.39	1.3	0.9	
	Various locations inside vault	0.34	4.6	0.2	
2-68	Vault survey	0.63	0.69	4.2	
	Vault survey	0.72	0.62	4.5	
	Vault survey	0.84	0.37	3.9	
	Vault survey	0.59	0.48	2.1	
	Vault survey	0.64	0.88	1.1	
	Vault survey	0.67	0.64	3.7	
2-69	Vault survey	0.63	0.59	2.9	
	Vault survey	0.59	0.59	2.2	
	Vault survey	0.67	0.67	3.2	
	Outside vault in adjoining rooms	0.41	2.7	0.36	
	Outside vault in adjoining rooms	0.47	2.6	0.20	
	Outside vault in adjoining rooms	0.33	2.7	0.13	
2-70	Outside vault in adjoining rooms	0.83	2.5	0.20	

BUILDING 231 VAULT (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
3-39	Near container	1.53	0.15	11	3.0
	At end of rack near 2 man area	0.58	0.75	3.3	3.0
	End of first rack	1.11	0.24	8.4	7.0
	Center of racks	0.58	0.7	3.1	3.0

BUILDING 281 REACTOR

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
1-39	Through tube entrance	0.146	34	1.14	
	North of diff. experiment entrance	0.176	20	0.09	
	N of radiography in line with thermal collimator shutter open	0.36	3.2	0.7	
	N of radiograph in line with thermal collimator shutter closed	0.24	8.4	0.03	
	North of shutter	0.36	3.4	0.3	
	West of thermal column	0.29	13	0.5	
	Inside NERF door inline with shutter	0.28	1.0	14.4	
	Inside NERF door north of shutter	0.23	1.8	8.5	
	West thermal column	0.29	12.7	0.5	
	S.W. neutron diffraction spectrometer	0.18	19.7	0.1	
	South through tube	0.18	18.0	12.8	
1-40	In cave	0.15	28	7.2	6.0
	Doorway to cave	0.24	33	0.5	0.15
	Table top at far wall	0.22	21	0.2	0.14
	Center of entrance to cave	0.21	20	0.7	0.17
	Shield S.E.	0.20	14	0.1	0.14
	Shield S	0.29	18	0.04	0.14
	Near far wall S.	0.18	20	0.09	0.15
	Near reactor S.W. side	0.14	16	0.05	0.14
	Near reactor west end in beam line	0.20	16	0.07	0.16
	Near reactor west end further from reactor	0.20	12	0.4	4.0
	Near reactor west end off beam line	0.23	13	0.2	2.0
1-41	Entrance to cave on N.W.	0.28	24	0.07	1.4
	Outside cave N.W.	0.19	19	0.04	0.16
	Outside cave N.W.	0.12	15	0.03	0.14
	Locations around beam tube	0.29	7.3	0.1	0.14
	Locations around beam tube	0.15	18	0.03	0.15
	Locations around beam tube	0.17	7.9	0.2	0.15
	Locations around beam tube	0.21	12	0.04	0.12
	Locations around beam tube	0.9	26	0.02	0.1
	Near Shield N.E.	0.22	8.0	0.9	0.12
	Near Shield E	0.15	4.3	0.4	0.13
	Top of reactor S	0.19	7.0	0.13	3.0
	Top of reactor E	0.18	4.3	0.12	4.0
	Top of reactor N	0.13	13	0.08	1.0
1-85	At thermal column	0.63	3.3	2.4	8.0
	South through port	0.19	16.4	13.0	9.0
2-76	Radiography port at end, port open	0.21	1.0	13.6	6.0
	Through port	0.17	18.3	12.1	6.0
	Thermal column, west	0.24	52.0	0.55	
3-60	South through port	0.20	6.8	123	40

BUILDING 281 REACTOR (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
3-61	South through port	0.17	8.6	46	14
3-62	South cave	0.18	16	13	6.0
3-63	South cave	0.16	15	16	9
3-64	Inside cave	0.15	21	6.4	3
	East cave, beside door	0.20	3.6	14	6

BUILDING 332

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
1-8	Hallway outside old vault	0.34	4.3	0.6	
	Hallway outside old vault	0.38	3.7	0.8	
	Hallway outside old vault	0.31	4.1	0.6	
	Hallway outside old vault	0.48	2.7	1.1	0.6
	Hallway outside old vault	0.42	3.3	1.0	0.6
	Hallway outside old vault	0.46	2.4	0.9	0.5
	Hallway outside old vault	0.37	3.4	0.9	
	Offices opposite old vault	0.36	5.6	0.4	0.2
	Offices opposite old vault	0.32	7.5	0.1	0.15
	Offices opposite old vault	0.45	3.9	0.1	0.1
	Offices opposite old vault	0.42	5.2	0.2	0.15
	Offices opposite old vault	0.46	4.2	0.4	0.3
	Offices opposite old vault	0.38	7.0	0.1	
1-13	Hallway opposite old vault	0.37	3.4	0.9	
1-16	Rm 1314 (room outside vault) near vault	0.32	4.3	0.4	
	Rm 1314 (room outside vault) near vault	0.38	2.8	0.6	
	Rm 1314 (room outside vault) end opposite vault	0.41	3.7	0.3	
	Rm 1314 (room outside vault) end opposite vault	0.35	4.5	0.1	
	Inside old vault in room 1314	0.67	0.8	9.2	
	Inside old vault in room 1314	0.63	0.7	10.4	
	Inside old vault in room 1314	0.62	0.8	8.8	
	Inside old vault in room 1314	0.79	0.6	12.3	
	Inside old vault in room 1314	0.82	0.6	13.4	
	Inside old vault in room 1314	0.60	1.0	7.3	
	Inside old vault in room 1314	0.58	0.9	8.2	
1-21	Inside old vault in room 1314	0.63	0.9	8.8	
	Inside old vault in room 1314	0.81	0.5	14.4	
	Outside old vault in room 1314 on table near vault	0.44	2.8	0.7	
1-33	Room 1378 Survey around box on south	0.68	0.9	0.2	
	Room 1378 Survey around box on south	0.62	0.9	0.3	
	Room 1378 Survey around box on south	0.78	0.6	0.4	
	Room 1378 Survey around box on south	0.85	0.6	0.4	
	Room 1378 Survey around box on south	0.93	0.3	0.6	
	Room 1378 Survey around box on south	0.73	0.6	0.4	
	Room 1378 Survey around box on south	0.81	0.4	0.4	
	Room 1378 Survey around box on south	0.74	0.8	0.2	
	Room 1378 Survey around box on south	0.83	0.4	0.7	
	Room 1378 Survey around box on south	0.68	0.7	0.5	
	Room 1378 Survey around box on south	0.78	0.6	0.5	
	Room 1378 Survey around box on south	0.91	0.4	0.9	
	Room 1378 Survey around box on south	0.75	0.6	0.4	
	Room 1378 Survey around box on south	0.65	0.9	0.2	

BUILDING 332 (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	γ
2-5	Hallway near old vault	0.46	2.8	1.2	
	Desk in office near vault	0.42	5.8	0.17	
	Inside vault	0.86	1.3	29.2	
	Inside vault	0.87	1.3	29.0	
	Inside vault	0.91	1.3	22.9	
	Inside vault	0.90	1.1	23.5	
	Inside vault	0.92	1.6	23.1	
2-6	Room 1314 at deck	0.35	4.9	0.14	
	Room 1378 survey around boxes	1.1	3.0	9.2	
	Room 1378 survey around boxes	0.20	2.7	4.5	
	Room 1378 survey around boxes	0.97	3.3	2.3	
	Room 1378 survey around boxes	1.17	1.9	1.8	
	Room 1378 survey around boxes	1.13	3.8	1.8	
2-7	Room 1378 survey around boxes	1.10	4.0	2.8	
	Room 1378 survey around boxes	1.02	2.2	3.0	
	Room 1378 survey around boxes	0.82	1.1	1.03	
	Room 1378 survey around boxes	1.26	1.5	4.0	
	Room 1378 survey around boxes	0.87	3.4	1.3	
	Pit in 1354 ∿1.5 ft	1.08	4.8	28.5	
2-8	Second Pit in 1354	0.74	6.4	13.0	
	Old vault	0.97	2.1	47.3	
	Old vault	0.90	1.4	24.3	
	Old vault	0.90	1.8	22.8	
2-56	Room 1362, pit and turnings	1.05	0.27	1.3	
2-62	Room 1372, 9" from burn box on south	0.65	1.1	0.43	
2-63	Desk in room 1314	0.47	2.1	0.59	
	Second desk in room 1314	0.73	3.8	0.15	
2-64	Office near old vault, on desk	0.40	5.3	0.09	
2-66	Room 1378, 15" from edge of bird cage	0.98	0.46	4.4	
	Room 1378, top of can	1.26	0.31	14.3	
2-71	Room 1378 box survey Pu in cans	1.84	0.12	19.1	
	Room 1378 box survey Pu in cans	0.96	0.47	3.3	
	Room 1378 box survey Pu in cans	0.85	0.68	2.2	
	Room 1378 box survey Pu in cans	0.98	0.53	2.7	
2-93	W-79, 18" center to center	0.88	0.28	3.5	
	Room 1379 box survey	1.34	0.67	3.5	
	Room 1379 box survey	1.30	0.68	3.5	
2-126	Castings in furnace room 1370	0.85	0.43	0.77	
	Castings in furnace room 1370	0.80	0.71	0.63	

BUILDING 332 (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
3-33	Storage vault 1314A	0.68	0.8	5.0	
	Storage vault 1314A	0.80	0.57	6.3	
	Storage vault 1314A	0.66	0.81	4.8	
	Storage vault 1314A	0.66	0.95	3.9	
3-34	Storage vault 1314A	0.66	0.81	4.3	
	Storage vault 1314A	0.66	0.95	3.9	
3-35	Outside storage vault, 1314	0.59	1.4	0.9	
	Outside storage vault, 1314	0.37	2.8	0.14	
3-36	Room 1378 near source storage	0.97	0.39	12.4	9.0
	On top of freezer, room 1378	0.53	1.2	0.7	1.7
3-37	1378 near source storage	0.95	0.33	20	9.0
	On deep freeze	0.57	1.2	1.3	3.0
3-38	1378 next to box	0.41	1.6	0.4	0.5
	1378 next to box	0.51	2.0	0.2	0.3
3-68	Room 1362, 5 KG of Pu in lathe	1.00	0.43	1.7	
3-69	Room 1377	1.05	0.37	3.4	
3-70	Room 1314	0.67	0.90	6.6	
3-73	Room 1330A, H&S tech office	0.77	1.4	2.0	
3-90	Roses Lab casting	0.97	0.6	1.5	
3-111	U-235 part from Super Kukla	0.73	0.36	1.0	
3-114	Hemishells room 1362, 18 inches	1.3	0.15	0.4	13
	Hemishells room 1362, 4 feet	0.80	0.5	0.06	1.3
3-114	New vault, desk, vault door closed	0.47	3.6	0.15	
	New vault, desk, vault door open	0.49	2.4	0.21	0.4
	At door to vault, door open	0.48	1.5	1.12	1.0
	At door to vault, door closed	0.56	1.3	4.1	1.0
3-116	Inside new vault	0.61	1.0	3.0	3.5
	Inside new vault	0.57	1.0	3.5	3.5
	Inside new vault	0.71	0.7	5.0	6.5
	Inside new vault	0.78	0.7	4.8	3.5
	Inside new vault	0.68	0.8	3.6	8.0
3-135	Survey in old vault	0.68	0.8	1.1	1.3
	Survey in old vault	0.58	0.9	0.7	0.8
	Survey in old vault	0.56	0.8	0.72	1.8

BUILDING 332 (continued)

Reference	Location	9/3 ratio	% Thermal	dose Rates n	dose Rates γ
3-136	Survey of hall outside old vault	0.42	3.9	0.1	
	Survey of hall outside old vault	0.50	2.9	0.1	
4-52	Measurement of Pu parts	1.73	0.016	3.2	
	Measurement of Pu parts	1.45	0.05	0.9	
4-92	Assembly on table top 18"	1.61	0.06	1.9	2
	Assembly on table top 9"	1.73	0.03	8.0	16
	Assembly on table top 12"	1.74	0.07	4.9	7
4-93	Assembly on table top 24"	1.43	1.2	1.2	2.5
	With mock HE 12"	1.27	0.10	4.5	8
	In Al stand 18"	1.03	0.36	1.5	0.6
	On floor in shipping container 12"	0.77	0.36	9.5	
5-69	Room 1314 survey	0.92	1.2	0.45	0.3
	Room 1314 survey	0.82	1.4	0.19	0.05
	Room 1314 survey	0.71	1.4	0.21	0.05
	Room 1314 survey	1.3	1.1	0.27	0.07
	Room 1314 survey	0.88	0.9	0.18	0.03
	Room 1314 survey	0.61	1.0	0.60	0.09
5-114	Survey in room 1314 3ft from door	0.56	1.4	0.26	0.4
	Survey in room 1314 center of room	0.61	1.8	0.14	0.15
5-135	Room 1329, heat sources stored next door	0.33	2.9	1.2	1.2
	Room 1329, heat sources stored next door	0.35	3.0	1.1	1.1
	Room 1329, heat sources stored next door	0.38	2.7	0.75	0.8
	Room 1329, heat sources stored next door	0.34	2.9	2.9	2.9
	Room 1329, heat sources stored next door	0.31	4.1	0.5	0.5
	Room 1329, heat sources stored next door	0.35	3.0	0.67	0.2
	Room 1329, heat sources stored next door	0.36	3.6	0.34	0.2
5-137	Room 1345, box with source	0.77	0.37	24	2.0
	Room 1345, box to right	0.51	1.0	9.3	0.5
	Room 1345, box to left	0.44	0.9	7.1	0.35
	Room 1345, second box to left	0.33	1.8	2.1	0.2
	Room 1345, center of room	0.53	1.2	3.8	0.2

APPENDIX C CALIBRATION PROCEDURES

A. Personnel Dosimeter (neutron)

Calibration of the natural Li or ^{6}Li TLDs used in the personnel badge is performed on a routine basis by the Dosimetry Group by exposing the TLDs to ^{137}Cs. No extra calibration is required. When a positive reading of the badge for neutrons is indicated, (reading of natural Li or ^{6}Li is >1.2 times the ^{7}Li or 20 mR cm greater than the ^{7}Li readings), the Health Physicist determines the proper calibration factor from Fig. 1 or 2 and divides the excess natural Li or ^{6}Li reading over the ^{7}Li reading by this factor to obtain the neutron dose. The Health Physicist enters the neutron dose on the exposure investigation sheet which is returned to the Dosimetry Group following review by the Health Physics Group Leader.

B. Albedo Dosimeter

The albedo neutron dosimeters have a calibration procedure different from the personnel dosimeter. Because of changes in the type of TLD material and other factors the calibration procedures for the time prior to November 1981 differ from those employed after November 1981.

1. Calibration procedures used before November of 1981

Prior to November 1981 the ^{6}Li TLDs used in the albedo dosimeters were used only in the albedo dosimeters (and some special studies). The calibration procedure consisted of four exposures as follows: (1) the primary neutron calibration consisted of two albedo dosimeters (each containing two ^{6}Li and two ^{7}Li TLDs) exposed to the bare Cf source at one meter for one hour, (2) a secondary neutron calibration by exposing two albedo dosimeters to 500 mrem from the 10 cm polyethylene moderated Cf source at one meter, (3) two albedo dosimeters exposed to 50 mR and, (4) 500 mR of ^{137}Cs gamma rays at two meters. The Cs calibrations were averaged and used to normalize the readings of the two types of TLDs to correct for differences in their sensitivity to gamma-rays. The readings of the ^{7}Li TLDs are subtracted from the ^{6}Li TLD reading to obtain the neutron response of the TLDs. The neutron response from the bare Cf source is divided by the neutron dose to obtain the calibration factor.

The results from the monthly calibration were plotted to assure that no change in TLD sensitivity, reader response, or other factors had occurred. Curves were plotted of the (1) calibration factor for the bare Cf source, (2) neutron readings of TLDs (^{6}Li minus ^{7}Li) exposed to the bare Cf, and to the (3) 10 cm polyethylene Cf source, and (4) the gamma reading of the ^{7}Li TLDs exposed to the Cf source for one hour.

The memo attached to this report as Appendix B uses a calibration factor of 0.125 as a basis for evaluating the 9/3 ratio. Over the past few years the calibration factors from the monthly calibrations have been within ±10% of 0.125 (with only one flyer). As long as the monthly calibration factor was close to 0.125 no correction for TLD or reader sensitivity changes was applied to the albedo dosimeter results. The calibration factors for the albedo dosimeter were assigned based on where the individual would be working or if this was not known, 1.00 was assigned.

The results for the monthly badges were reviewed by Dale Hankins to assure that; (1) the TLD readings did not contain flyers (comparison of the readings of the two TLDs of each type in the dosimeter), (2) the calibration factor was appropriate for the persons job, (3) a calibration factor was assigned where 1.00 had been used to indicate the appropriate factor was not known at the time of issue, and (4) a comparison was made of the readings of the natural Li TLD (minus ^{7}Li TLD) in the personnel badge and the albedo results to see if both measurement techniques agreed reasonably well.

2. Calibration procedure used after November 1981

In November 1981 the ^{6}Li TLDs in the albedo dosimeter were changed, and are the same TLDs used in the personnel badge. In addition the value used for the dose rate of the californium source at one meter was changed. The new ^{6}Li TLDs have less sensitivity than the old ^{6}Li TLDs by x 0.795. The new value for the Cf sources was higher than the previously used value by x 1.145. In addition, the phototube on the TLD reader was changed during September and some adjustments were made to the readout cycle. This resulted in an increase in the neutron sensitivity compared to the gamma sensitivity of about 24%.

The present calibration procedure consists of exposing two albedo dosimeters to 500 mRem of bare Cf neutrons; two are exposed to 100 mR of Cs and two are exposed to 500 mR of Cs. Four additional TLDs are exposed for quality control purposes to the 5 cm D_2O moderated Cf source. These dosimeters could be used as a secondary calibration if necessary.

It is recommended that the present calibration procedure be changed to increase the bare Cf source exposure from 500 to 1000 mRem or more, to give better dosimeter statistics. It is also recommended that a secondary neutron calibration be provided which would be used to verify the primary calibration or replace it if lost.

Variations in the sensitivity of the TLDs, changes in reader sensitivity and other factors which result in a change in the monthly calibration can be handled in two ways. The first is to change the calibration factor applied for each individual and the second is to adjust the calculated dose. The second technique is preferred since it is easier to make a change in the final calculated dose for the few persons exposed each month than to attempt to change the calibration factor for all personnel. This factor was determined as a result of considerable data being obtained over several years (see Appendix B) and is based on a calibration factor of 0.125. It is felt that to change the persons calibration factor each month would result in confusion and eventually errors in determination of the appropriate calibration factor.

It is recommended that if the monthly calibration changes are less than ±10% (from 0.125) no correction be made. If the monthly calibration change indicates >10%, the secondary calibration should be checked confirming that the change is real and not the result of flyers. If the change is real, the dose calculated for that person should be adjusted accordingly.

A review of the monthly badge results similar to the one discussed in the previous section should be performed.

Interdepartmental letterhead

Mail Station L- 383

Ext: 25171

February 28, 1978

TO: Distribution

FROM: D. E. Hankins

SUBJECT: Calibration factors for albedo neutron dosimeters

The calibration factor for albedo neutron dosimeters is a strong function of the neutron energy. This factor can be determined by two techniques. The first is to place TLDs on an appropriate phantom (gallon jug for dosimeters worn on the chest) and expose them to a known dose (usually determined by using a 9-in. dia. sphere remmeter). The reading of the TLDs (Li-6 minus Li-7) is divided by the measured dose to obtain the appropriate calibration factor.

The second technique is to use the ratio of readings obtained with the 9-in. sphere remmeter and the reading obtained by placing the remmeter probe into a 3-in. 10-mil Cd covered sphere. The latter sphere has a response which is very similar to the energy dependence of an albedo neutron dosimeter being worn by an individual. The 9-in. sphere remmeter has a response to neutrons over a large energy region which is approximately proportional to the neutron dose rate. The ratio of the readings of the 9- to 3-in. spheres is used with the curve shown in Fig. 1 to obtain the calibration factor. Because this second technique (ratio of 9- to 3-in. sphere) is easier and faster, it is preferred. The neutron reading of the TLDs (Li-6 minus Li-7) of the personnel badge is <u>divided</u> by the calibration factor to obtain the neutron dose.

Differences in the calibration factors determined by the two techniques occur (especially if the neutrons are impinging isotropically vs. frontally) and these are discussed at the end of this report.

The ratio of the 9- to 3-in. sphere has been obtained at most locations at LLL where personnel neutron exposures may occur. The calibration factor for the albedo neutron dosimeters was determined using the curve shown in Fig. 1. The calibration factors (as a function of dose rate) have been plotted in Figs. 2-10 for the various Laboratory buildings. Although the calibration factors may have a large variation, it has been found in most cases that within a single facility the variation is small and an average calibration factor can be applied. At the upper left corner of each of the figures we give an average calibration factor for that facility. Some of the figures for the facilities are rather complex and therefore each is discussed separately.

Building 332

The results obtained in Building 332 are plotted in Figs. 2, 3, and 4. Figure 2 shows the points obtained in room 1378, work with a small PuBe source, and for large pieces of Pu such as castings, hemishells, pits, and one device. The points fall into three categories. The first is work with PuBe sources where a calibration factor of 0.2 is applied (see also Figs. 8 and 10). The second is work with large quantities of Pu where a factor of 0.3 is applied and third, work in room 1378 (except PuBe work) where a factor of 0.4 applies.

Figure 3 shows the results obtained in both the old and new vaults. A calibration factor of 0.4 should be applied for this work (see also Fig. 5). Figure 4 shows the results obtained in room 1378 during work with PuBe residues. The lower calibration factor of 0.2 results from the higher energy PuBe neutrons when compared to fission neutrons from Pu.

To apply the appropriate factor it is important that we know when PuBe sources are being used in the building or when someone not normally working in the vaults spends significant time (>1 day) in the vaults.

Building 231 Vault

The calibration factors vary greatly in Building 231 (see Fig. 5) and vary as a function of distance from the source container. The two points with the highest dose rate are not typical exposure conditions with measurements having been made close to the container. The lower dose rates were obtained at the south end of the vault and contribute little to the exposure of personnel. The bulk of the remaining points are typical of most exposure conditions and a calibration factor of 0.45 was selected for the vault exposures.

Building 233

The neutron storage area of Building 233 and the adjoining vault and offices are shown in Fig. 6. For work in the storage area the higher dose rate points would be responsible for most of the exposure. Since the personnel may also work in the Building 231 vault (see Fig. 5) it was decided to also use 0.45 for this building. By doing this, in some cases, exposures may be slightly overestimated, especially those occuring in the office area.

Building 212 - ICT

The data points in Fig. 7 are divided into two categories with the data obtained on top of the ICT shielding being separated from the remainder of the results. The ICT points included data taken throughout Building 212, around the ICT shielding and at the surrounding buildings. An average calibration factor of 0.9 should be applied for all areas except the roof, where a value of 0.5 applies.

Building 251

The data points obtained in Building 251 are shown in Fig. 8. Considerable spread in the points exists with the points near the bottom of the figure being from unshielded or poorly-shielded sources and those at the center and top being from sources in the shielded caves. For the caves, a calibration factor of 0.8 should be applied. When the work involves bare sources of Cm a calibration factor of 0.3 applies. For work above, below, or behind a shielded cave containing Cm a factor of 0.3 also applies. Work with bare Cf-252 sources should have a factor of 0.2 applied (see also Table II). Because the calibration factors for Building 251 vary greatly, it will be necessary to know what type of work the individual was performing each month for us to apply the correct calibration factor.

Building 281

Figure 9 shows the points obtained around the reactor in Building 281. An average calibration factor of 1.8 was selected based on the higher dose rate points. Because this factor is much larger than for the other buildings, an exposure occuring at the reactor would be significantly overestimated if a calibration factor for the other buildings is applied. The opposite applies if a reactor assigned albedo is worn at another building. Care should be taken to assure that appropriate calibration factors are applied.

Buildings 255, 131 and Site 300

Figure 10 shows a number of points taken at Building 255, Site 300 and Building 131, but the results apply to similar exposure conditions at any facility. The PuBe results are from a source in air, in a bucket of paraffin, and in a very large cask. Similar results for a shielded PuBe source are in Fig. 2 (Building 332) and Fig. 8 (Building 251). From these data the calibration factor of lightly shielded PuBe source would be 0.2. For unshielded PuBe sources the factor is 0.1. Heavily shielded PuBe has a calibration factor of 0.35.

Cf sources in heavy shields appear at the higher dose rates in Fig. 6 (Building 233), Fig. 8 (Building 251), and in Fig. 10. From these a calibration factor of 0.4 was determined. For lightly shielded Cf-252 a factor of 0.3 should be applied and for unshielded Cf the factor is 0.14 (see Table II).

One data point was obtained at the door to A cell in Building 255 while the Cf source was in the cell. The calibration factor is 1.0 and would apply to exposures received near this door or at the console.

One device was measured at Building 131 and the calibration factor of 0.23 is in agreement with the value of 0.3 obtained at Building 332 (see Fig. 2). The 131 value had very little scattered neutron and in most cases a value of 0.3 would apply.

Three points were measured at Site 300 behind a berm shield for an accelerator. Although the results are for a limited number of points, the results are in general agreement with the ICT results (Fig. 7) and a calibration factor of 0.8 appears reasonable.

Moderated sources in Building 255

In Tables I and II we show the results obtained with moderated PuBe and Cf sources, respectively. The calibration factors vary greatly for the various moderators, becoming larger as the moderator size is increased. There is also an increase as the distance from the source is increased. The scattering conditions in Building 255 are small compared to those existing in most field applications and therefore represent a lower value for the calibration factor with the typical field condition being higher. The PuBe source has an average neutron energy higher than the Cf source and the calibration factors are always lower for PuBe.

For the monthly calibration of the personnel albedo neutron dosimeters we will be using the 10-cm poly moderator with the Cf source. Exposures will be at 50 and 500 mrem. The exposure times will be about 12 minutes and three hours at 1 meter from the source and the readings of the TLD 700 will be about 15 and 150 mR.

The readings of the TLD 600 will be about three times as large as the TLD 700 readings. This moderator-source combination falls off the calibration curve and is shown as the "calibration point" in Fig. 1. Although this point lies off the curve, it is reproducible and will be used to correct for monthly variations in the TLD responses when they occur.

Calibration factor determination

To determine the calibration factor for an individual's exposure, if possible, the calibration factor should be determined by using the readings of the 9- and 3-in. spheres. Readings should be obtained at the point where the exposed individual was working, with the neutron source in position. The ratio of the 9- to 3-in. spheres is determined and Fig. 1 used to obtain the appropriate calibration factor. In most cases, however, the opportunity to make measurements will not exist and it will be necessary to find similar exposure conditions in Figs. 2-10 and apply that calibration factor, or if the exposure conditions varied or are not known, use the averaged factor for the building (summarized in Table III).

For the cases where the individual is not aware of why or where the exposure occurred, additional information can be obtained by reading the TLD-100 in his TLD badge. A positive reading will confirm a real exposure, and the size of the reading, compared to the albedo reading, can sometimes be used to evaluate both dosimeters. See Dale Hankins for assistance in these cases.

There are several types of errors which can occur in interpreting the albedo neutron dosimeter. The first is the selection of an inappropriate calibration factor. This can be caused by not knowing the exposure conditions or by selecting the wrong factor. In most cases, if reasonable care is used, this will not result in a serious over- or underestimate of the exposure. A second error occurs when the person is exposed from a direction other than the front; i.e., isotropically, back, side, etc. For an exposure from the back (the worst case) the interpreted dose could be as low as 1/3 the actual dose. Since most work with neutron sources is done with the worker facing the source, this normally is not a serious source of dosimetry error. A third type of error applies for very low energy neutrons (mostly reactor leakage neutrons) where the energy dependence of the 9-in. sphere causes its readings to be high (up to $\sim$90% at a power reactor). Since the 9-in. sphere is the basis for determing the neutron dose rate and the calibration factor is based on the ratio of the 9- to 3-in. sphere, the readings of the albedo neutron dosimeter will be high by the same amount as the 9-in. sphere. A correction for this overresponse will be made for exposures occurring at LLL.

Modified Calibration Factor Curve

We have for years assumed that the shape of the curve in Fig. 1 is a straight line. While preparing the data for this memo I looked at the calibration factors that were obtained from badges planted on phantoms and compared these to the calibration factor obtained by using the 9- to 3-in. sphere ratio. The results were plotted in Figs. 11 and 12. In Fig. 11 are shown the results obtained using the moderated sources in A cell of Building 255 and three points from the NBS work. Figure 12 shows the results obtained elsewhere. In both figures a straight line was drawn at equal, observed, and 9/3-in. sphere calibration factors. Above a calibration factor of 1.2 the observed calibration factors deviate from this line, being consistantly larger. Another line has been drawn through these points which would give a reasonable fit to the field results (Fig. 12). This curve was then applied to Fig. 1 resulting in the curve indicated "revised 2/3/78." In the future, this curve should be used since it gives a better fit to observed field results.

The points in Fig. 12 show the spread in the results determined by using results from badges placed on gallon jugs vs. the 9/3-in. ratio to determine the calibration factor. In Fig. 13 lines have been drawn at the extremes and indicated that the two techniques usually agree within ± 30%. At the lower calibration factors, low readings of up to 50% were observed. At these points the neutrons were known to be approximately isotropic and a low calibration factor was expected from the badge results.

From Fig. 13 one can infer that the calibration factor obtained by using the 9/3-in. sphere ratio is accurate to within ± 30%. This agreement confirms the usefulness of the 9/3-in. sphere technique to determine calibration factors.

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Table 1. PuBe results obtained using the moderators in Building 255.

Moderator	Distance (meters)	Ratio 9/3	9/3 calibration factor	Observed calibration factor
None	1	2.44	0.10	0.103
	2	1.47	0.18	0.164
2-cm poly	1	1.64	0.16	0.21
	2	1.14	0.23	0.25
5 cm poly	1	1.23	0.22	0.31
	2	0.94	0.29	0.33
10 cm Poly	1	1.13	0.23	0.35
	2	0.84	0.33	0.40
25 cm H_2O	1	1.18	0.22	0.33
	2	0.86	0.32	0.37
5 cm D_2O	1	1.13	0.23	0.24
	2	0.81	0.34	0.32
10 cm D_2O	1	0.61	0.47	0.56
	2	0.55	0.53	0.64
15 cm D_2O	1	0.37	0.83	1.17
	2	0.34	0.91	1.06
25 cm D_2O	1	0.31	1.00	1.66
	2	0.29	1.08	1.50
20 cm Al	1	1.17	0.23	0.20
	2	0.81	0.34	0.27

Table II. Cf results obtained using the moderators in Building 255

Moderator	Distance (meters)	Ratio 9/3	9/3 calibration factor	Observed calibration factor
None	1	1.78	0.14	0.137
	2	1.15	0.23	0.226
2 cm poly	1	1.09	0.24	0.30
	2	0.81	0.34	0.37
5 cm poly	1	0.76	0.37	0.55
	2	0.57	0.51	0.58
10 cm poly	1	0.68	0.42	0.67
	2	0.54	0.54	0.66
25 cm H_2O	1	0.77	0.36	0.50
	2	0.59	0.49	0.49
5 cm D_2O	1	0.77	0.36	0.37
	2	0.58	0.50	0.44
10 cm D_2O	1	0.38	0.80	0.98
	2	0.35	0.89	0.99
15 cm D_2O	1	0.23	1.42	2.00
	2	0.22	1.49	1.83
25 cm D_2O	1	0.18	1.87	3.50
	2	0.18	1.87	2.70
20 cm Al	1	0.94	0.29	0.24
	2	0.64	0.44	0.33

Table III. Summary of calibration factors for the various buildings at LLL.

Building 332	
Room 1378	0.4
Other rooms	0.3
Vaults	0.4
Room 1378 during PuBe work	0.2
Shielded PuBe work	0.2
Building 231 Vault	0.45
Building 235	0.45
ICT - Building 212	0.9
Top of ICT shielding	0.5
Building 251	
Shielded boxes	0.8
Unshielded work	
^{244}Cm tracers	0.3
^{252}Cf tracers	0.2
Boxes (top-bottom-no shield)	0.3
Building 281 - Reactor	1.6 *
Buildings 255, 131 and Site 300	
Shielded sources	
^{252}Cf	0.4
PuBe	0.2
Unshielded sources	
^{252}Cf	0.14
PuBe	0.1
Berm shielded accelerator	0.8
255 Control room	1.0

*An addition correction for the overresponse of the 9-in. sphere will have to be applied.

Figure 1. Curve showing the ratio of the 9/3-in. sphere as a function of the calibration factor for albedo neutron dosimeters (Hankins type). (1/31/78)

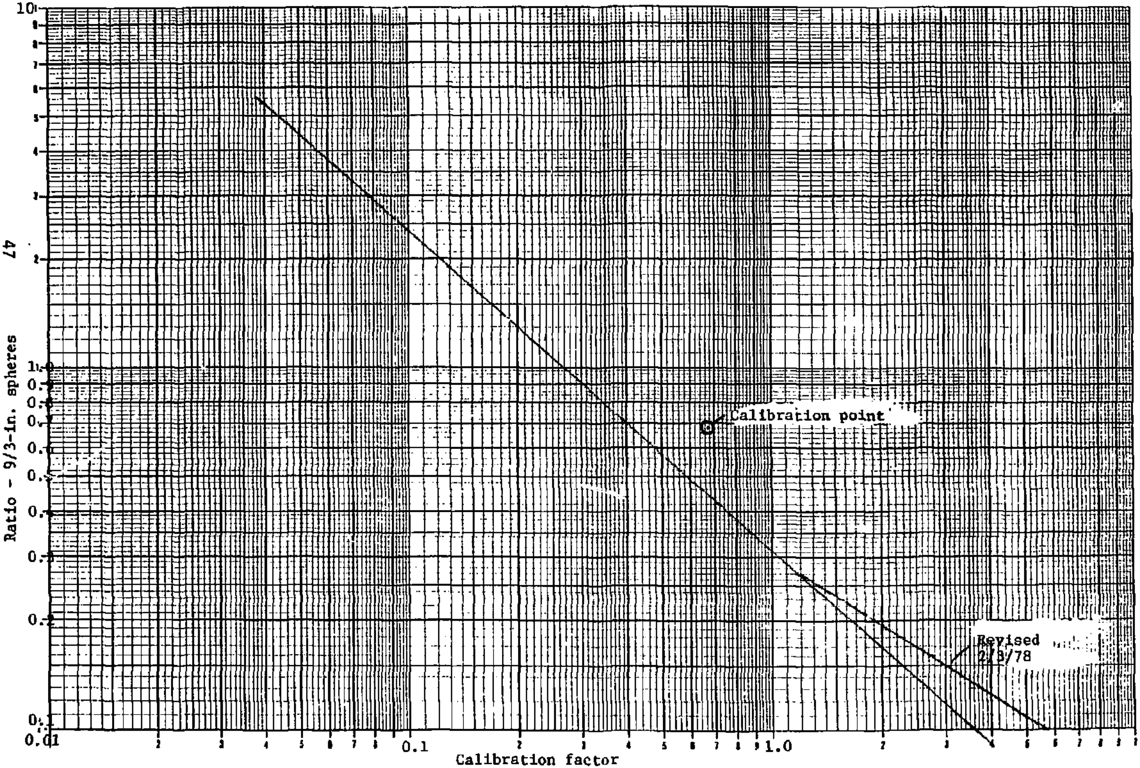


Fig. 2, Bldg 332 (except vaults & Rm 1378 during PuBe work)

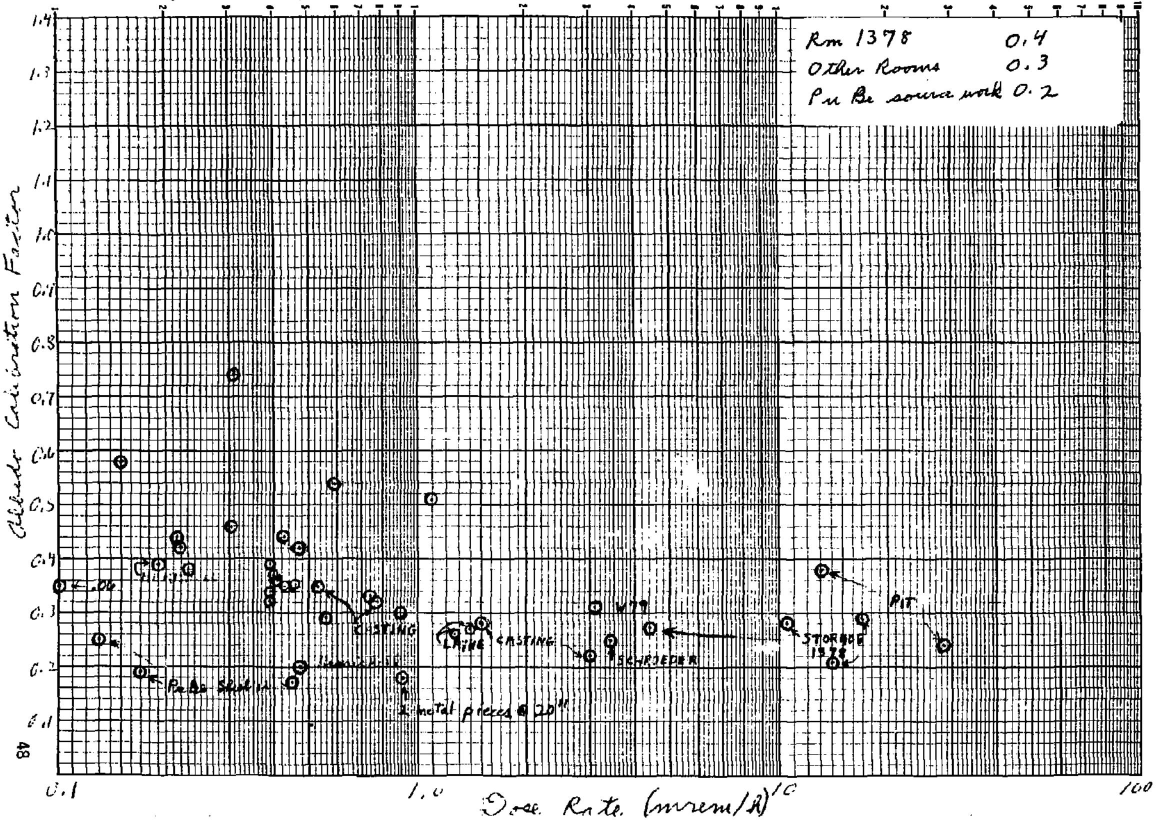


Fig. 3 Bldg 332 Vaults (INSIDE)

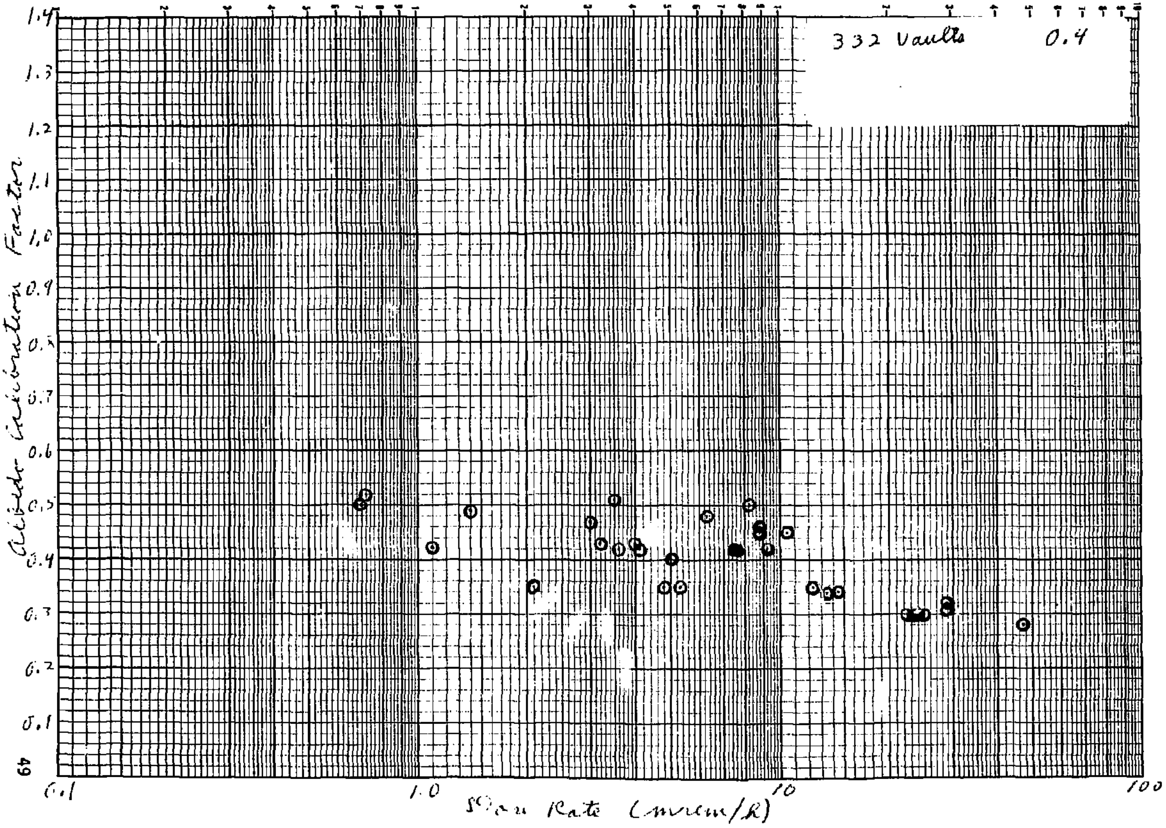


Fig. 4. Rm 1378 Bldg 332 (during PuBe work)

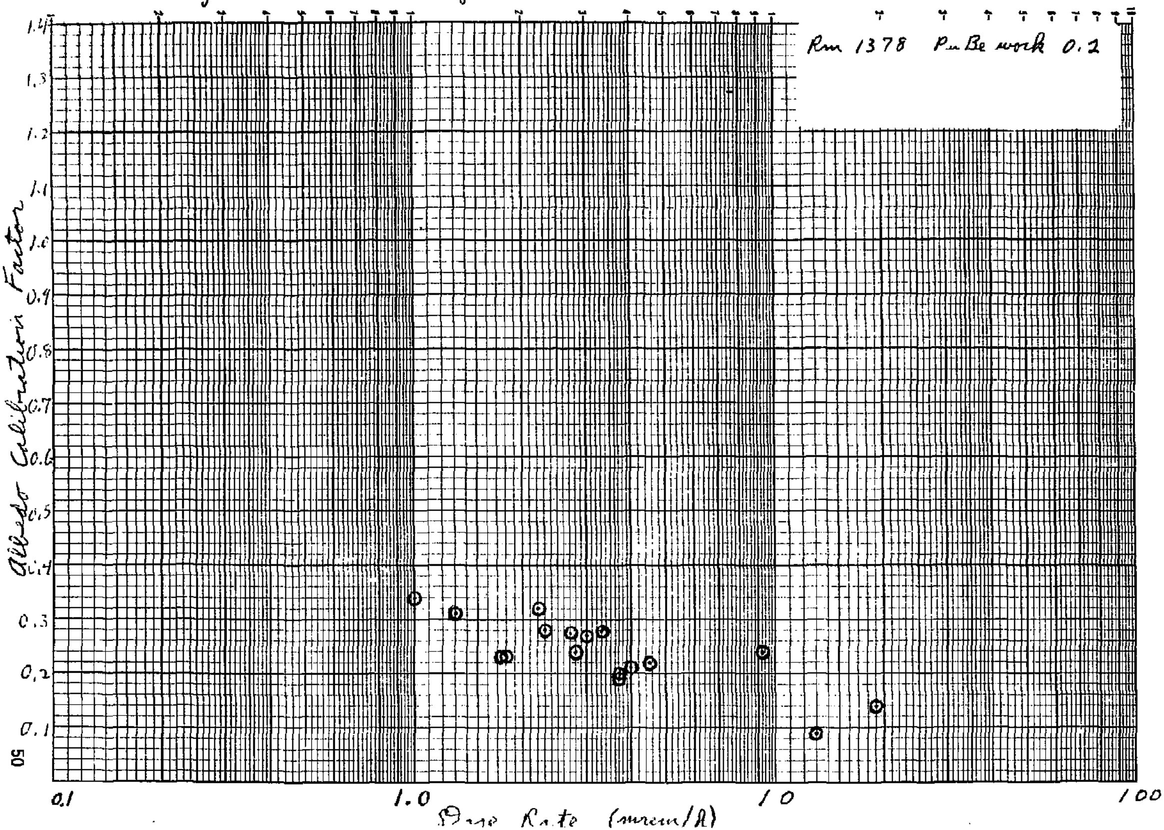
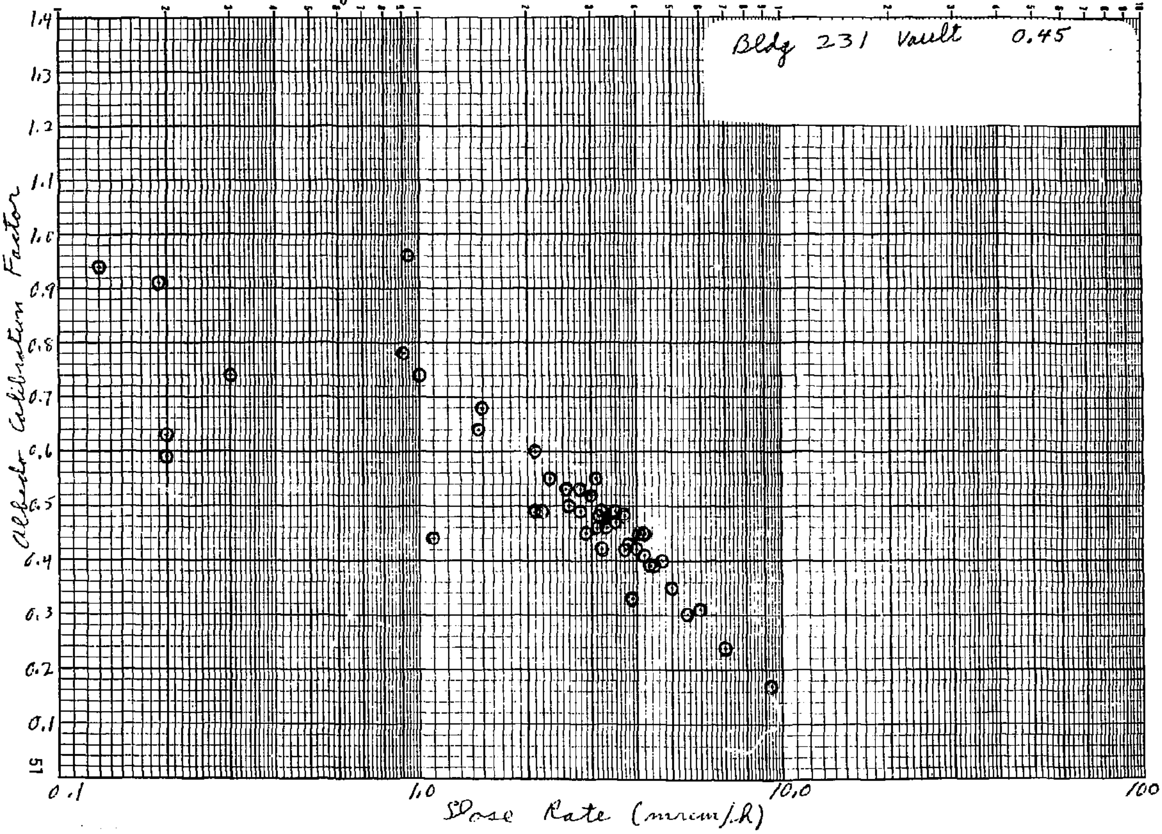


Fig. 5. Bldg 231 Vault



GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York SEMI-LOGARITHMIC 3 CYCLES X 70 DIVISIONS

Fig. 6. Bldg 233

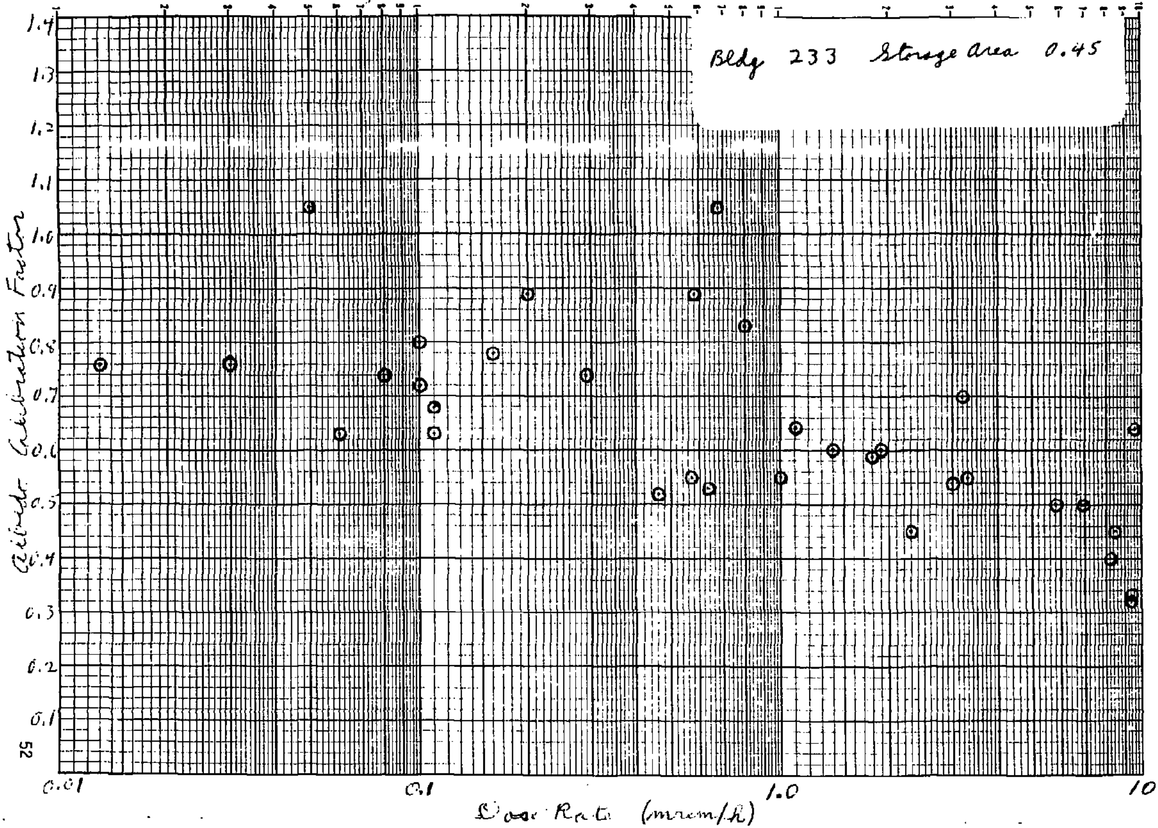
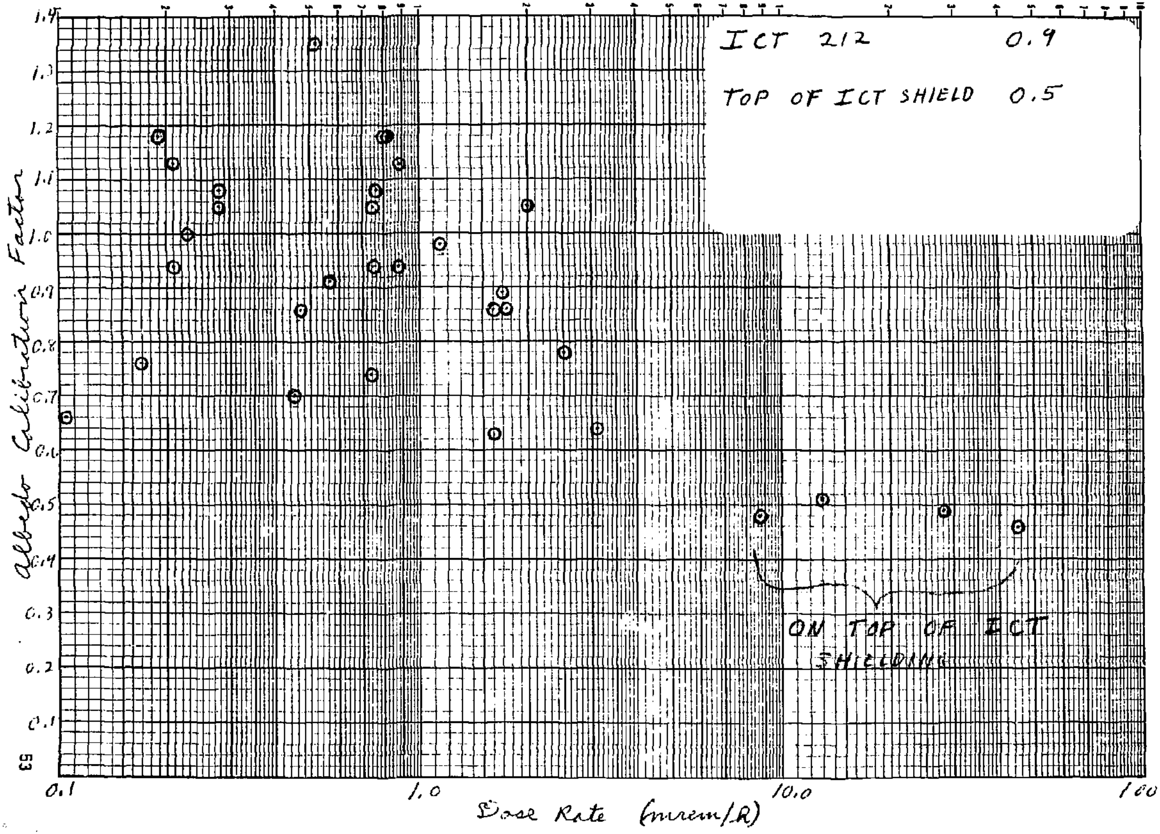


Fig. 7. ICT-212



ICT 212 0.9
TOP OF ICT SHIELD 0.5
ON TOP OF ICT SHIELDING
Albedo Calibration Factor
Dose Rate (mrem/R)
0.1
1.0
10.0
100
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

Fig. 8. Bldg 251

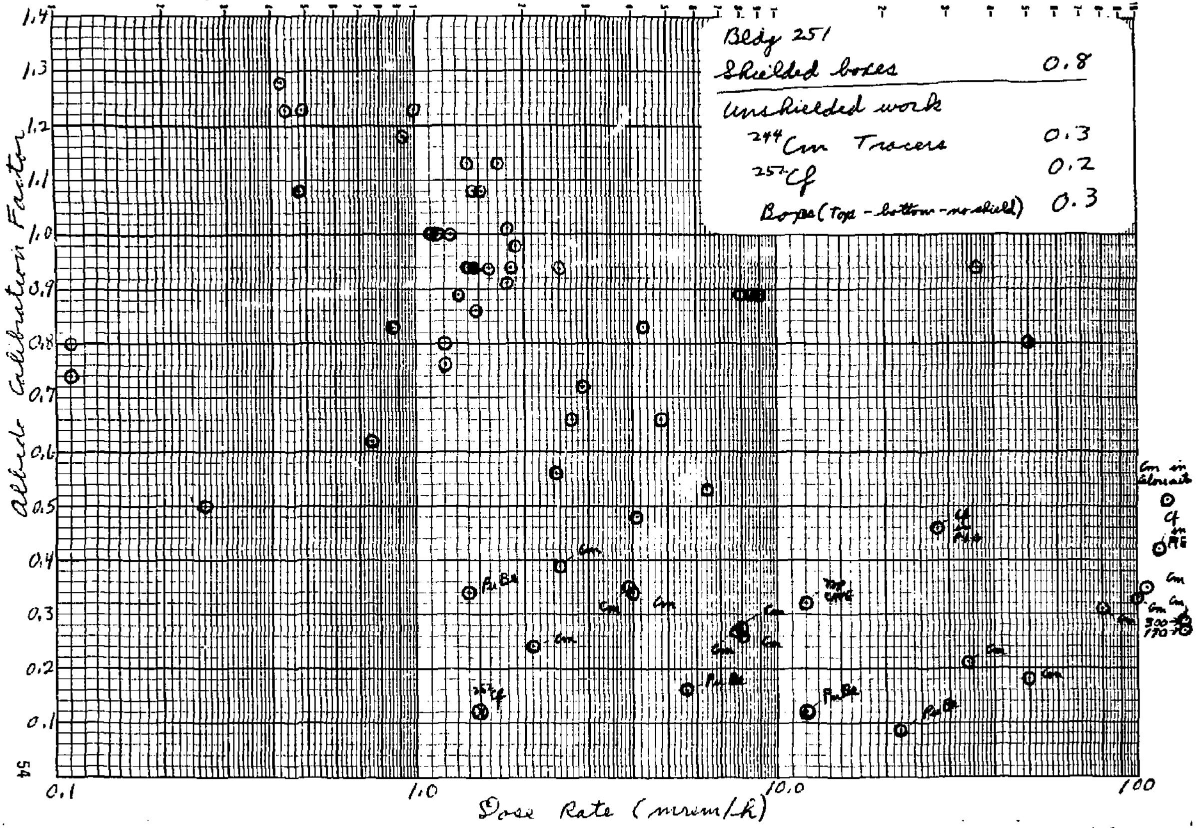


Fig. 4. ⊙ Bldg 281 Reactor

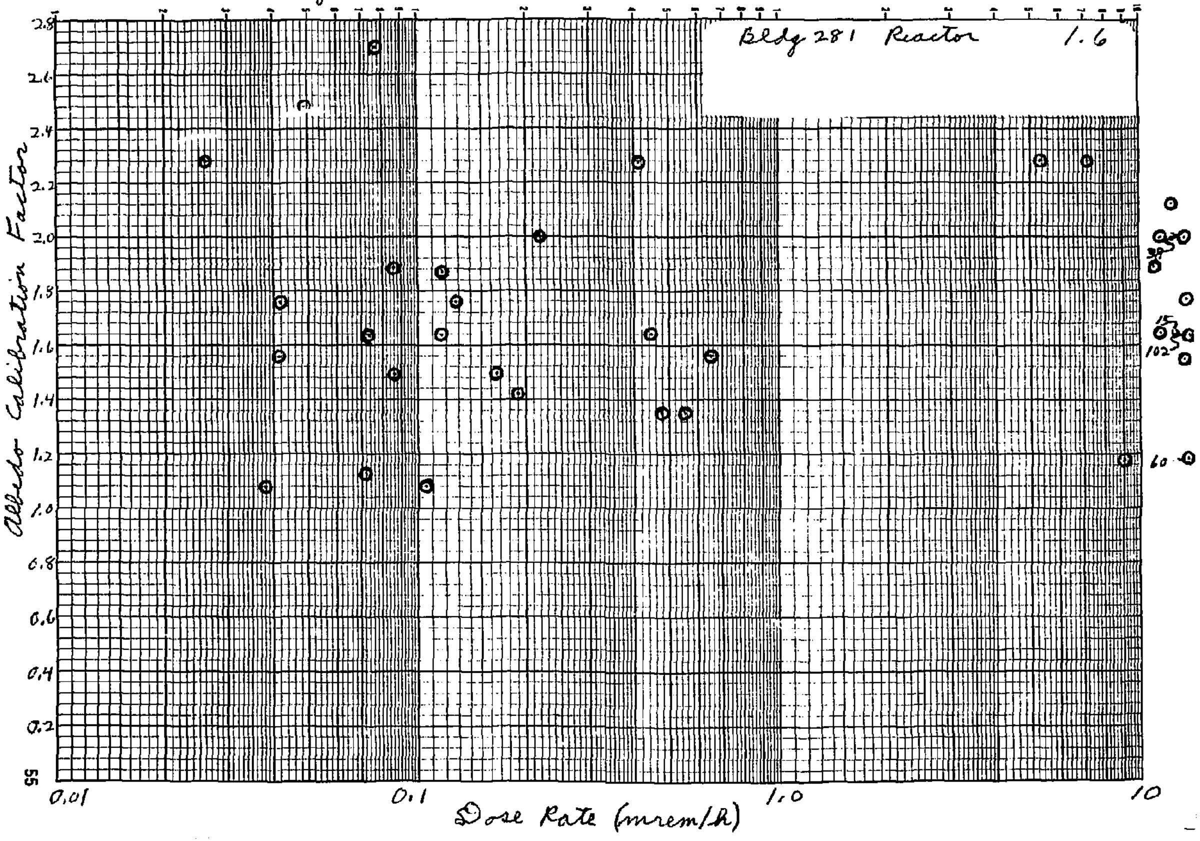


Fig. 10. Bldg 255 & Bldg 131 + Site 300

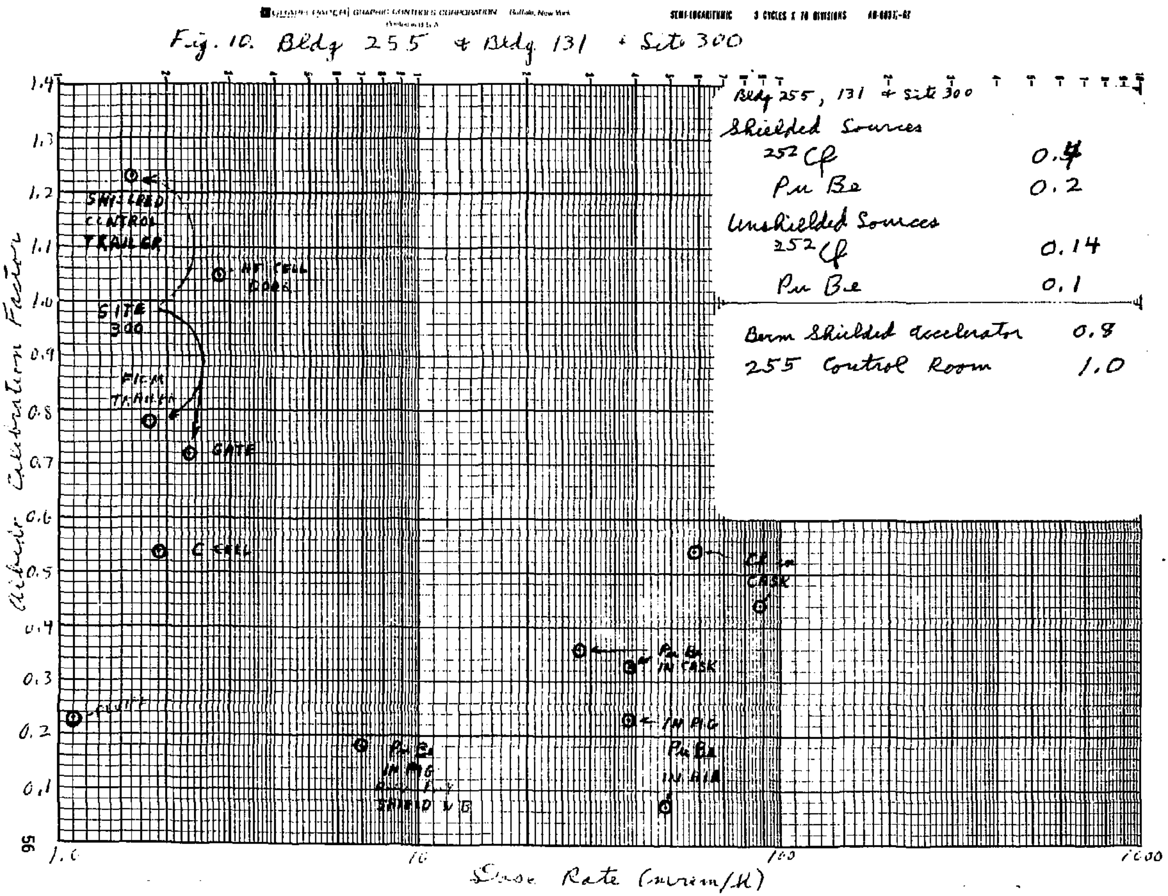


Fig. 11.

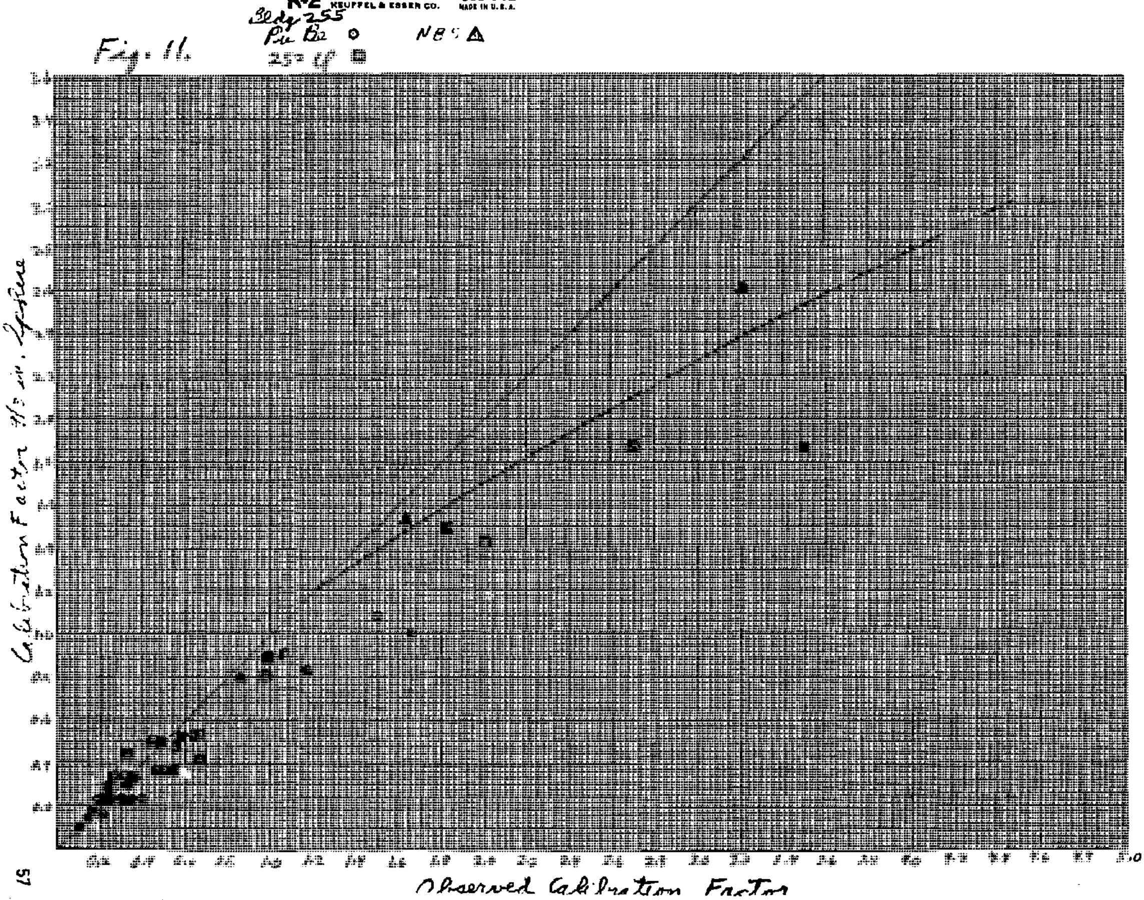

Bldg 255
Pu Be ○
NBS △
252 Cf □
Calibration Factor 45 in. Sphere
Observed Calibration Factor

Fig. 12.

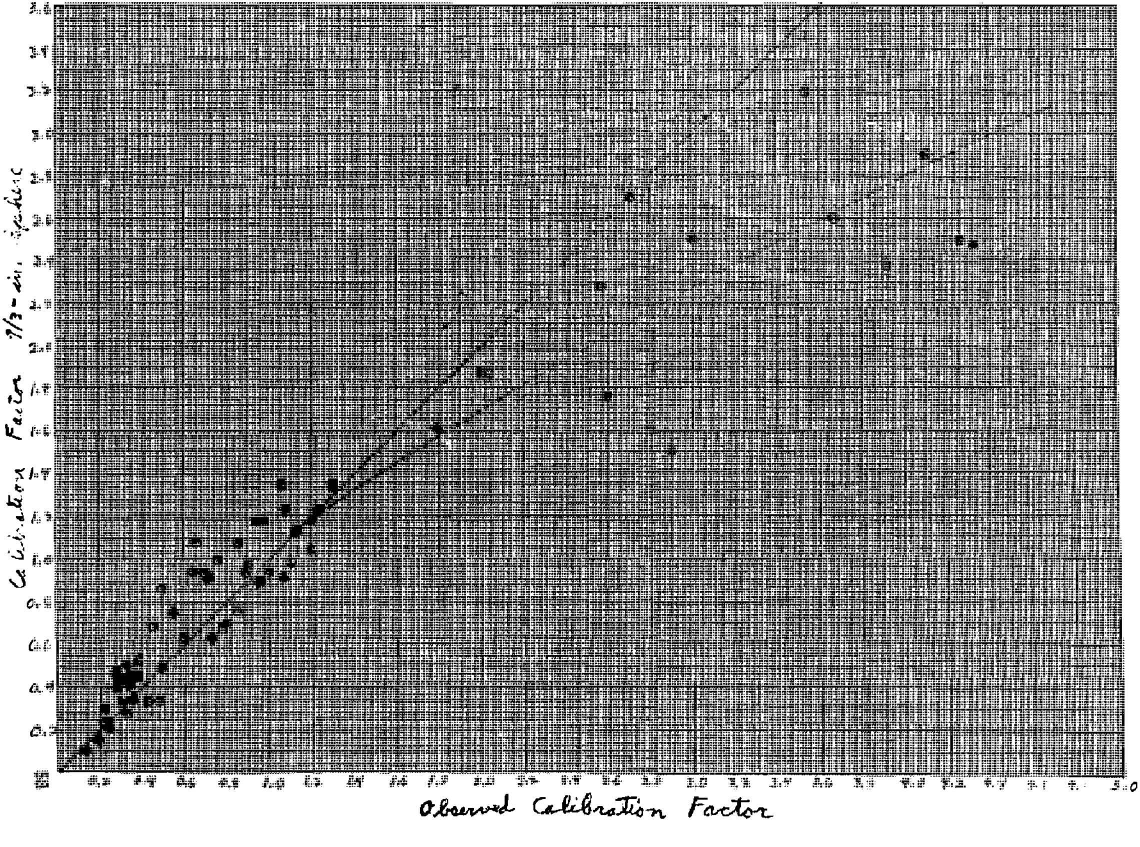

Calibration Factor 9/3-in. sphere
Observed Calibration Factor
5.0

Fig 13. Curves showing the size of the error made by assuming the 9/3- in. sphere calibration factor is correct and using that factor to evaluate the dosimeter.