Table 1.e. Background doses and dose rates for all measurements: Nagatomo et al. 1992: Hiroshima

Lab	Place and sample	Sample ID#	RERF list No.	Sample type	Beta (mGy/y)	±	Gamma (mGy/y)	±	Total (mGy/y)	±	Age (y)	±	Total bkg dose (Gy)	±	Dose to:	Reported dist (m)
NUE	Hiramoto Oni-gawara	A1-1		Tile					2.22		48		0.107	0.110	tissue	2053
NUE	Hiramoto Oni-gawara	A1-2		Tile					2.22		48		0.107	0.110	tissue	2053
NUE	Hiramoto Oni-gawara	A1-3		Tile					2.22		48		0.107	0.110	tissue	2053
NUE	Hiramoto Oni-gawara	A2		Tile					2.30		48		0.110	0.011	tissue	2053
NUE	Hiramoto Oni-gawara	A3		Tile					2.53		48		0.121	0.007	tissue	2053
NUE	Hiramoto Oni-gawara	A4-1		Tile					2.22		48		0.107	0.011	tissue	2053
NUE	Hiramoto Oni-gawara	A4-2		Tile					2.22		48		0.107	0.011	tissue	2053
NUE	Hiramoto Oni-gawara	A5		Tile					2.22		48		0.107	0.007	tissue	2053
NUE	Kirihara	B1-1		Tile					2.12		66		0.140	0.015	tissue	2453
NUE	Kirihara	B1-2		Tile					2.12		66		0.140	0.015	tissue	2453

Table 1.f. Background doses and dose rates for all measurements: Nagatomo et al. 1995: Hiroshima

Lab	Place and sample	Sample ID#	RERF list No.	Sample type	Beta (mGy/y)	±	Gamma (mGy/y)	±	Total (mGy/y)	±	Age (y)	±	Total bkg dose (Gy)	±	Dose to:	Reported dist (m)
NUE	Postal Savings (Chokin Kyoku)	A		Tile	2.10	0.17	0.78	0.04	2.88	0.18	49		0.141	0.009	tissue	1591
NUE	Postal Savings (Chokin Kyoku)	A		Tile	2.08	0.07	0.90	0.02	2.99	0.07	49		0.147	0.003	tissue	1604
NUE	Postal Savings (Chokin Kyoku)	A		Tile	2.03	0.06	0.76	0.03	2.78	0.06	49		0.136	0.003	tissue	1605
NUE	Postal Savings (Chokin Kyoku)	A		Tile	2.00	0.02	1.01	0.03	3.00	0.03	49		0.147	0.001	tissue	1613
NUE	Postal Savings (Chokin Kyoku)	A		Tile	1.97	0.10	0.86	0.06	2.83	0.11	49		0.139	0.005	tissue	1631

Table 1.g. Background doses and dose rates for all measurements: Maruyama and Kumamoto, this work: Hiroshima

Lab	Place and sample	Sample ID#	RERF list No.	Sample type	Beta (mGy/y)	±	Gamma (mGy/y)	±	Total (mGy/y)	±	Age (y)	±	Total bkg dose (Gy)	±	Dose to:	Re-ported dist (m)
JNIRS	Hiroshima University Radioisotope Facility			Tile	2.29	0.16	1.25	0.04	3.54	0.16	63	0	0.22	0.01	tissue	1462
JNIRS	Hiroshima University Radioisotope Facility			Tile	2.29	0.16	1.25	0.04	3.54	0.16	63	0	0.22	0.01	tissue	1497
JNIRS	Hiroshima University Radioisotope Facility			Tile	2.29	0.16	1.25	0.04	3.54	0.16	63	0	0.22	0.01	tissue	1469
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1451
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1451
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1451
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1451
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1451
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1501
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1501
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1501
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1501
JNIRS	Red Cross Hospital			Tile	2.34	0.16	1.21	0.07	3.55	0.17	55	2	0.20	0.01	tissue	1501

Table 1.g. Background doses and dose rates for all measurements: Maruyama and Kumamoto, this work: Nagasaki

Lab	Place and sample	Sample ID#	RERF list No.	Sample type	Beta (mGy/y)	±	Gamma (mGy/y)	±	Total (mGy/y)	±	Age (y)	±	Total bkg dose (Gy)	±	Dose to:	Re-ported dist (m)
JNIRS	Nagasaki University Hospital			Tile												655
JNIRS	Nagasaki University Hospital			Tile												655
JNIRS	Nagasaki University Hospital			Tile												655
JNIRS	Sakamoto Cemetery			Brick	2.95	0.38	1.05	0.06	4.00	0.38	57	2	0.23	0.02	tissue	1039
JNIRS	Sakamoto Cemetery			Brick	2.95	0.38	1.05	0.06	4.00	0.38	57	2	0.23	0.02	tissue	1039
JNIRS	Sakamoto Cemetery			Brick	2.95	0.38	1.05	0.06	4.00	0.38	57	2	0.23	0.02	tissue	1039
JNIRS	Sakamoto Cemetery			Brick	2.95	0.38	1.05	0.06	4.00	0.38	57	2	0.23	0.02	tissue	1039
JNIRS	Nagasaki University Charnel			Brick	1.8	0.11	1.05	0.06	2.85	0.13	79	3	0.23	0.01	tissue	1435
JNIRS	Nagasaki University Charnel			Brick	1.8	0.11	1.05	0.06	2.85	0.13	79	3	0.23	0.01	tissue	1435
JNIRS	Nagasaki University Charnel			Brick	1.8	0.11	1.05	0.06	2.85	0.13	79	3	0.23	0.01	tissue	1435
JNIRS	Yamada Oil Storehouse			Brick	1.87	0.13	1.1	0.04	2.97	0.14	87	12	0.26	0.04	tissue	2043
JNIRS	Yamada Oil Storehouse			Brick	1.87	0.13	1.1	0.04	2.97	0.14	87	12	0.26	0.04	tissue	2043
JNIRS	Yamada Oil Storehouse			Brick	1.87	0.13	1.1	0.04	2.97	0.14	87	12	0.26	0.04	tissue	2043
JNIRS	Yamada Oil Storehouse			Brick	1.87	0.13	1.1	0.04	2.97	0.14	87	12	0.26	0.04	tissue	2043
JNIRS	Yamada Oil Storehouse			Brick	1.87	0.13	1.1	0.04	2.97	0.14	87	12	0.26	0.04	tissue	2043
JNIRS	Yamada Oil Storehouse			Brick	1.87	0.13	1.1	0.04	2.97	0.14	87	12	0.26	0.04	tissue	2043
JNIRS	Yamada Oil Storehouse			Brick	1.87	0.13	1.1	0.04	2.97	0.14	87	12	0.26	0.04	tissue	2043

Japan Institute of Radiological Sciences

Sampling. The RERF has usually collected bricks or decorative tiles for TL measurements from exposed buildings that were scheduled to be dismantled, after receiving the owners' permission. In spite of the cooperation of the citizens in Hiroshima and Nagasaki and the efforts of staff and researchers of RERF and Hiroshima University, it was difficult to collect enough ceramic samples to represent all locations in the entire zones less than 2.5 km from the hypocenters in both cities. Fortunately, however, several decorative tile plates were provided from three different buildings in Hiroshima, and several tile plates and brick blocks from five buildings in Nagasaki. The characteristics of ceramic samples are given in Table 2.

Sample Preparation. The goals of sample preparation for atomic-bomb dosimetry are fourfold:
Step 1: To isolate a TL material of sufficient sensitivity to allow measurement of the doses of interest.
Step 2: To provide a homogeneous material with respect to TL output, avoiding competing TL components from unwanted minerals.
Step 3: To provide homogeneous TL materials that had experienced throughout, as closely as possible, the same radiation history with respect to alpha, beta, gamma, cosmic rays and atomic-bomb radiation.
Step 4: To accomplish this without increasing, decreasing, or introducing spurious components into the TL signal.

Table 2. Decorative tile and brick samples provided by RERF and Hiroshima University to JNIRS after DS86

City	Building	Ground distance	Sample type	Year of construction	Year of measurement	Building age*
Hiroshima	Hiroshima University Science Buildings	1,277 to 1,469 m	Tiles	1935	1997	62 yr
	Koudou Primary School	720 m	Tiles	1924	not measured	not measured
	Teishin Hospital	1.370 m	Tiles	1935	not measured	not measured
	Red Cross Hospital	1,413 to 1,501 m	Tiles	1939	1994	56 yr ?
Nagasaki	University Hospital Tower	655 m	Tiles	1902	1991	56 yr
	Sakamoto Cemetery Family Graveyard Gatepost	1,039 m	Bricks	1935	1992	57 yr
	Nagasaki University Charnel House	1,435 m	Bricks	1912	1991	79 yr
	Yamada Oil Storehouse, exterior (bomb fluence)	2,043 m	Bricks	1904-1928 1903-1912	1990 ?	75 yr 92-98 yr
	Yamada Oil Storehouse, interior (control)	2,043 m	Bricks	1904-1928 1903-1912	1990 ?	75 yr 92-98 yr

*The estimated age at time of measurement, which varies among samples.

TL Measurements. In TL gamma-ray dosimetry using ceramic materials, the two most often used methods of analysis are the “quartz inclusion” or “high temperature” technique, and the “pre-dose” technique. Readers interested in a detailed description of TL measurements should refer to the DS86 Final Report (Maruyama et al. 1987).

Background Measurements. A TL dating technique used in archaeology has been applied to the present dose estimation for gamma rays from the atomic bombs. The basic notion of TL dating is that firing of pottery by ancient man resets the TL clock to zero and that during the subsequent decades or centuries, the trapped electron population builds at a uniform rate due to low-level ionizing radiation provided by natural radioactivity in the clay of the pottery and in the soil in which the pottery was buried after the archaeological site fell into disuse. Similarly, bricks and tiles cumulate TL energy due to ionizing radiation emitted from natural radionuclides at a constant rate (Figure 2). In addition to the background TL due to natural radionuclides, the bricks and tiles in Hiroshima and Nagasaki accumulated TL energy from the atomic-bomb radiation in 1945. Since the gamma-ray dose at a distance of more than 1 km from the hypocenter can be expected to be very small, the evaluation of background radiation is important for dose estimation.

The background dose is contributed by natural radioactivity included in and around ceramic samples, primarily the ^{235}U, ^{238}U, and ^{232}Th series and ^{40}K and ^{87}Rb, as well as cosmic rays. Dose rates for alpha, beta, gamma, and cosmic rays must be included or excluded depending on the TL

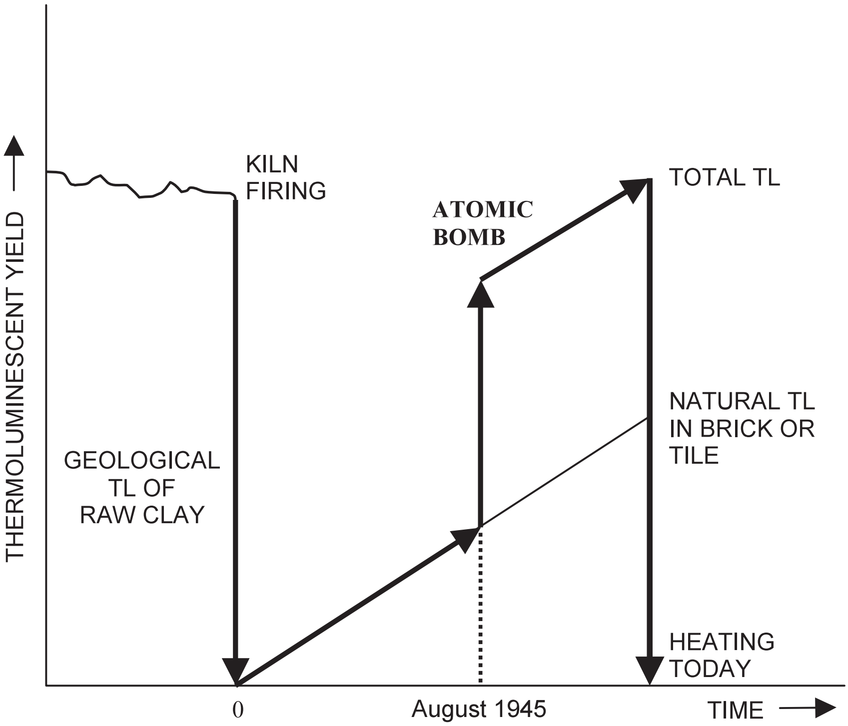

Figure 2. *Illustration of thermoluminescent dating from Maruyama et al. (1988).*

technique applied. One approach to excluding alpha background that is suitable for large quartz crystals (~100 μm) is to etch the surfaces of the prepared quartz crystals with hydrofluoric acid (HF). A carefully designed procedure of this type, which removes a thin layer of about 10 microns, removes the material containing most of the dose received from alpha particles emitted from the ^{235}U, ^{238}U, and ^{232}Th series radionuclides in the matrix of the sample adjacent to the quartz crystals, along with a portion of the beta background dose that compensates for the small portion of alpha dose that is not removed. This is part of the “improved quartz inclusion”technique used by the NUE-HU group (Nagatomo et al. 1991). Because the JNIRS group could not use HF etching for practical reasons related to safety, their “high temperature technique,” which uses higher-energy traps similarly to the “quartz inclusion” technique, does not exclude alpha background. Therefore, they did not use their high-temperature technique for samples with estimated bomb doses less than about 3 Gy in their DS86 and later work; rather, they used the “pre-dose” technique. In the pre-dose technique the effect of alpha radiation has been shown to be negligible. Furthermore, gamma spectrometry of samples has indicated that the types of ceramic materials used in atomic-bomb dosimetry in Hiroshima and Nagasaki, in contrast to some of those used in archeological dating, are not high in concentrations of alpha emitters (Maruyama et al. 1987, 1988).

The JNIRS and the NUE-HU groups measured the annual background dose rate of ceramic samples using a commercially available TL dosimeter. As an example of measurements, Table 3 gives annual beta background dose rates of ceramic samples in Hiroshima and Nagasaki (data from the JNIRS). These data were compared with previous data on other samples collected from the same buildings. Each difference between present and previous data is due not only to experimental errors but also differences in the composition of the ceramic materials. Although only one of the buildings measured is statistically significant with respect to the difference between previous and newer measurements of background, all of the differences are in the same direction. Possible causes for these differences are being considered. The procedure for measuring background has not changed since DS86. However, beta background is strongly dependent on individual sample composition, and although background is measured using samples from the same building as the samples used to measure atomic-bomb dose, there is some

Table 3. The background beta dose from brick samples measured in March 1999 by JNIRS

Site	Sample	Number of samples	Annual background dose, mGy/yr	S.D.
Hiroshima University RI Facility	T1-1	3	2.36	0.13
	T1-2	2	2.2	0.13
	T1-3	3	2.06	0.1
	Avg		2.29	0.16
Red Cross Hospital	T1-6	1	2.25	0.13
	T1-44	1	2.48	0.15
	T2-35	1	2.3	0.15
	Avg		2.34	0.16
Nagasaki University Charnel	B10	2	1.82	0.11
	B13	1	1.78	0.17
	B17	2	1.77	0.09
	Avg		1.8	0.11
Yamada Oil Storehouse	A	3	1.76	0.09
	B	3	1.99	0.1
	Avg		1.87	0.13

Comparison of measured (1999) and estimated (1986) beta dose

Site	Present annual background dose, mGy/yr		Previous annual background dose, mGy/yr		Previous minus Present annual background dose, mGy/yr
	Mean	S.D.	Mean	S.D.	
Hiroshima					
Hiroshima University RI Facility	2.29	0.16	2.65	0.32	0.36*
Red Cross Hospital	2.34	0.18	2.75	0.36	0.36*
Nagasaki					
Nagasaki University Charnel	1.8	0.11	2.5	0.35	0.7*
Yamada Oil Storehouse	1.87	0.13	2.95	0.14	1.08**

*Not statistically significant **Statistically significant variability of composition among individual samples from the same building. Also, the commercially supplied Mg_2SiO_4 TL powder used to measure beta background is not identical in composition to the quartz crystals in the samples.

The JNIRS group performed an *in situ* background measurement using 5 brick blocks of the room wall inside the Yamada oil warehouse. These brick samples were shielded by the 40 cm thick outside brick wall against atomic-bomb radiations. It was expected that a 40 cm thickness of bricks would attenuate the intensity of ^{60}Co gamma rays, for example, to a value less than one thirtieth of the unattenuated value. Because of this attenuation and the very low bomb dose at the distance of these samples (2,043 m, free-in-air DS02 kerma of 106 mGy), the measurement of these samples using the pre-dose technique would be expected to include no more than a few mGy of bomb-related dose. The average cumulative gross measured dose of these "control" bricks was 270 ± 50 mGy. This value agreed well with the background value estimated by the techniques normally used to measure background, 258 ± 38 mGy, as given in Table 1.g.

Results. Tables 4 and 5 give the results of new TL measurements by the JNIRS group. The supralinearity corrections for samples with non-negligible supralinearity are given in Table 6.

Hiroshima University and Nara University of Education

Measurements in Hiroshima were continued after the publication of the DS86 report. A particular effort was made to characterize dose at several key sites at longer distances, such as the Postal Savings Building (Chokin Kyoku) (Nagatomo et al. 1995), the Myosenji Temple (Hoshi et al. 1989), the Hiramoto residence (Hoshi et al. 1989; Nagatomo et al. 1992), and the Kirihara residence (Nagatomo et al. 1992). Where possible, such as at the Postal Savings Building, various samples from different parts of the site were measured. The results obtained are shown in detail in Table 1 of this section (background) and in the tables and analyses of Part B of this chapter.

Table 4. Gamma-ray doses from the atomic bomb in Hiroshima measured by JNIRS after DS86

Site	Ground distance, m	Total dose, Gy	S.D.	Beta dose, μGy/yr	S.D.	Gamma dose, μGy/yr	S.D.	Elapsed time, yr	S.D.	Bomb dose, Gy	S.D.
Hiroshima University RI Facility	1462	0.92	0.21	2290	160	1250	40	63	0	0.7	0.21
	1497	0.78	0.23	2290	160	1250	40	63	0	0.56	0.23
	1469	0.9	0.29	2290	160	1250	40	63	0	0.68	0.29
Red Cross Hospital	1451	0.93	0.14	2340	160	1210	70	55	2	0.73	0.14
	1451	1.02	0.15	2340	160	1210	70	55	2	0.82	0.15
	1451	0.95	0.12	2340	160	1210	70	55	2	0.75	0.12
	1451	0.99	0.12	2340	160	1210	70	55	2	0.79	0.12
	1451	0.94	0.13	2340	160	1210	70	55	2	0.74	0.13
	1501	0.93	0.14	2340	160	1210	70	55	2	0.73	0.14
	1501	0.81	0.13	2340	160	1210	70	55	2	0.61	0.13
	1501	0.9	0.11	2340	160	1210	70	55	2	0.7	0.11
	1501	0.94	0.15	2340	160	1210	70	55	2	0.74	0.15
	1501	0.86	0.11	2340	160	1210	70	55	2	0.66	0.11

Table 5. Gamma-ray doses from the atomic bomb in Nagasaki measured by JNIRS after DS86

Site	Ground distance, m	Total dose, Gy	S.D.	Beta dose, μGy/yr	S.D.	Gamma dose, μGy/yr	S.D.	Elapsed time, yr	S.D.	Bomb dose, Gy	S.D.
Nagasaki University Hospital	655	40.4	3.85							40.4	3.85
	655	33.4	3.94							33.4	3.94
	655	24.4	2.55							24.4	2.55
Sakamoto Cemetery	1039	6.5	0.84	2950	380	1050	60	57	2	6.27	0.84
	1039	5.18	0.89	2950	380	1050	60	57	2	4.95	0.89
	1039	6.21	0.43	2950	380	1050	60	57	2	5.98	0.43
	1039	6.76	0.59	2950	380	1050	60	57	2	6.53	0.59
Nagasaki University Charnel	1435	1.46	0.21	1800	110	1050	60	79	3	1.23	0.21
	1435	1.51	0.18	1800	110	1050	60	79	3	1.28	0.18
	1435	1.4	0.15	1800	110	1050	60	79	3	1.17	0.15
Yamada Oil Storehouse	2043	0.38	0.05	1870	130	1100	40	87	12	0.12	0.06
	2043	0.45	0.05	1870	130	1100	40	87	12	0.19	0.06
	2043	0.43	0.05	1870	130	1100	40	87	12	0.17	0.06
	2043	0.43	0.05	1870	130	1100	40	87	12	0.17	0.06
	2043	0.35	0.03	1870	130	1100	40	87	12	0.09	0.04
	2043	0.39	0.04	1870	130	1100	40	87	12	0.13	0.05
	2043	0.45	0.07	1870	130	1100	40	87	12	0.19	0.08

Table 6. Supralinearity corrections for post-DS86 measurements by JNIRS

	Ground distance, m	Gross dose, Gy	S.D.	Supralinearity, Gy	S.D.	Total dose, Gy	S.D.
Nagasaki University Hospital	655	38	3.4	2.4	1.8	40.4	3.85
	655	31	3.5	2.4	1.8	33.4	3.94
	655	22	2.4	2.4	1.8	24.4	2.55
Sakamoto Cemetery	1039	4.98	0.81	1.52	0.21	6.5	0.84
	1039	3.9	0.74	1.28	0.5	5.18	0.89
	1039	4.71	0.4	1.5	0.16	6.21	0.43
	1039	5.59	0.49	1.17	0.32	6.79	0.59

Uncertainty Analysis

Previous publications have included fairly detailed treatments of the uncertainty in gamma TL measurements of bomb fluence samples. A notable case in point is the material beginning on p. 149 of the DS86 Final Report (Maruyama et al. 1987). This material was carefully reviewed for the current effort. Several particular aspects of measurement uncertainty are considered in the following sections, either because they emerged as possible areas of concern in this review, or because they were raised in the recent report by the National Research Council (2001). Then, the overall uncertainty of the measurements is reviewed in light of these considerations and related calculations for all measurements considered in this work.

Background Doses

The measurement of background dose in TLD is of increasing importance with increasing distance from the hypocenter. TLD has the somewhat unusual aspect that background is measured separately on the same samples (beta background) or in the same location (gamma background) that are measured for bomb dose, but over a much shorter (typically about a factor of 1/100) period of accumulation than the total elapsed time since the firing of the sample. As the terms are used here, "beta" background dose rate relates to the dose rate that the measured material received *in situ* from beta emissions occurring in the matrix of the sample itself, from the naturally occurring radionuclides contained in the sample. "Gamma" background refers to penetrating radiations measured at the site of collection, including terrestrial gamma rays from naturally occurring radionuclides contained in the surrounding soils, rocks, and building materials; and cosmic rays. Thus "beta" background dose rates are a function of sample composition and are sample-specific, whereas "gamma" background dose rates are a function of local environment and are site-specific.

The available background measurements for all of the samples considered in this report are listed in Table 1. Almost all of the measurements reported in the DS86 Final Report and later have such estimates available. Total estimated background doses based on such measurements for samples of interest in Hiroshima and Nagasaki have been in a range from about 0.1 Gy to 0.33 Gy. The variability in these estimates depends primarily upon the measured beta background dose rate (Hiroshima 2.44 ± 0.61 mGy/y, Nagasaki 2.30 ± 0.48 mGy/y) and the age of the sample since firing (Hiroshima 54.3 ± 8.4 y, Nagasaki 67.9 ± 15.1 y). This contrasts with the samples used in the measurements of the 1960s, many of which were roof tiles thought to be several hundreds of years old, and therefore subject to an accumulated background dose of 1 Gy or more. They are not included in these tables because background measurements were not made for them—the original investigators had the philosophy that they would only be used to obtain results at distances where bomb doses would be so large that even such a background would represent only a small portion of the bomb dose. These measurements are included in the analysis of Part B of this chapter with new estimates of their background.

The gamma-ray background dose rate in samples for which it was measured (Hiroshima 1.07 ± 0.20 mGy/y, Nagasaki 1.08 ± 0.03 mGy/y) was less than half the size of the beta background dose rate on average, and had a standard deviation among measured sites about 1/3 as large as the beta background dose rate. (The averages and standard deviations quoted here are unweighted and are based on one measured value per location, for all of the available measurements considered in this work.)

The ground distances of corresponding calculated total free-field gamma dose from the bombs are about 1,900 m for 0.1 Gy and 1,600 m for 0.33 Gy in Hiroshima, or about 2,100 m for 0.1 Gy and 1,800 m for 0.33 Gy in Nagasaki. Estimated background begins to have a substantial effect on measured net doses at somewhat lesser distances than these, and uncertainty in background is a major contributor to the uncertainty of measured net doses at distances beyond about 1,500 m in Hiroshima or 1,700 m in Nagasaki.

In order to evaluate the potential effect of background dose estimates on the resulting net doses, all of the available information was assembled in a single table. The format of Table 2 of the TLD chapter in Volume 1 of the DS86 Final Report (Maruyama et al. 1987) was used as a template and was extended to include all newer measurements. All of the listed items of information were filled in as completely as possible by examination of previously published values and the new values presented in this work. The results are shown in Table 1.

For the evaluation of potential trends and for more general analysis, the measured annual dose rates are a more useful quantity than the calculated background doses, because they are free of the additional complications and uncertainties of the estimated ages of the materials since firing. Various statistical characterizations of the measured background dose rates might be of interest, but particularly interesting, in relation to the question of perceived trends in the related net doses vs. distance from the hypocenter, is a simple plot of the values as a function of distance. Such plots are shown in Figure 3, which eliminates duplication in the table and shows only the unique values for particular sites. A trend is apparent in the total background dose measured in Hiroshima, which is largely if not completely attributable to the beta component of background estimates. When the estimated total annual background dose rate is checked with a simple linear regression vs. distance, the result is a small negative slope that is statistically significant as differing from zero. This is an indication that the observed trend is unlikely to have arisen due to chance alone, if all of the background measurements were samples from a single statistical distribution with the same mean at all distances. The result holds even when the measured value at the distant location of the Ryomatsu sho (Army Provisions Warehouse: 3,387-m ground distance, 3.11 mGy/y), which is not shown on the plots, is included. A similar trend is not observed in Nagasaki, although the measurements there are considerably fewer and the power to detect a trend would therefore be less.

These results *per se* do not establish any conclusion regarding the measured net values. For example, if it happens that the compositions of the sample materials chosen for measurement were such as to have lower background values at longer distances for some reason having to do with the building materials used in various areas, there might be a *bona fide* trend in background vs. with distance. However, this would not create any artifact in the measured net values if the measurements of background were accurate.

On the other hand, if there is a source of bias in the background measurements due to changes in measurement technology over time as more distant samples were measured, or for some other reason, this could be a source of misleading results in the measured net values. Another point of interest in regard to possible trends in background is that the JNIRS group has noted as discussed above that their newer estimates of beta dose on some samples measured previously have given lower results than before. Although it is presently not possible to establish the nature and the cause of the apparent trend in background vs. distance, its appearance suggests that it should be carefully considered in any analysis of measured net dose vs. distance.

Energy Response and Calibration

The report by National Research Council (2001) raised the issue of the energy response of quartz TL to the gamma-ray spectrum of the bombs in contrast to the gamma-ray spectrum of the sources used to calibrate the assays by test irradiation. The DS86 Final Report itself noted on p. 147 that:

> As illustrated in Figure 4 quartz and other materials relevant to the present study are not tissue equivalent, particularly at low photon energies where the absorption coefficient, and thus the absorbed dose, increases as the cube of the atomic number of the absorber. The result for dosimetry purposes may be a severe overestimate of exposure if the low-energy component of the radiation is under estimated.

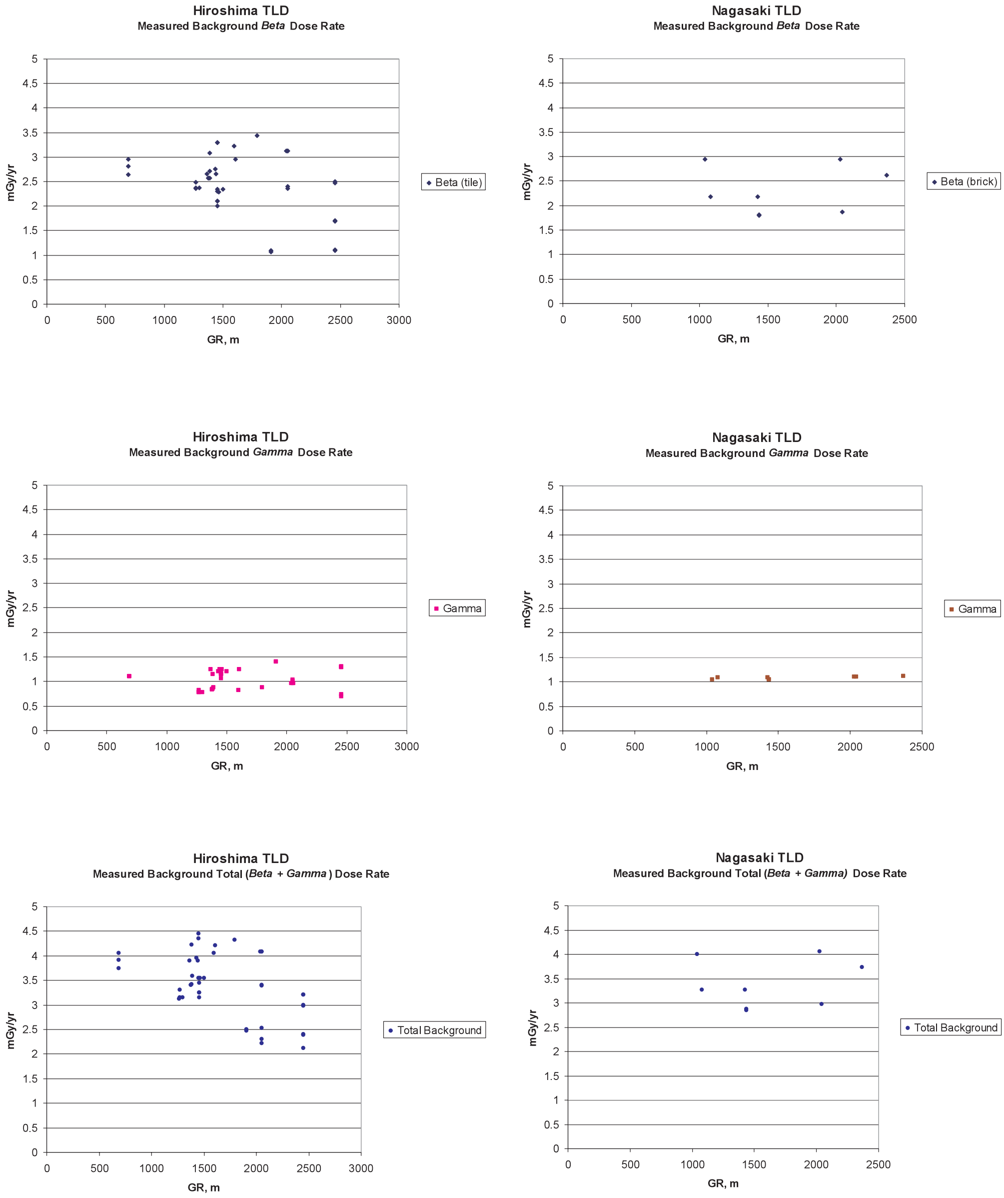

Figure 3. *Measured beta, gamma, and total background dose rates for TLD samples in Hiroshima and Nagasaki.*

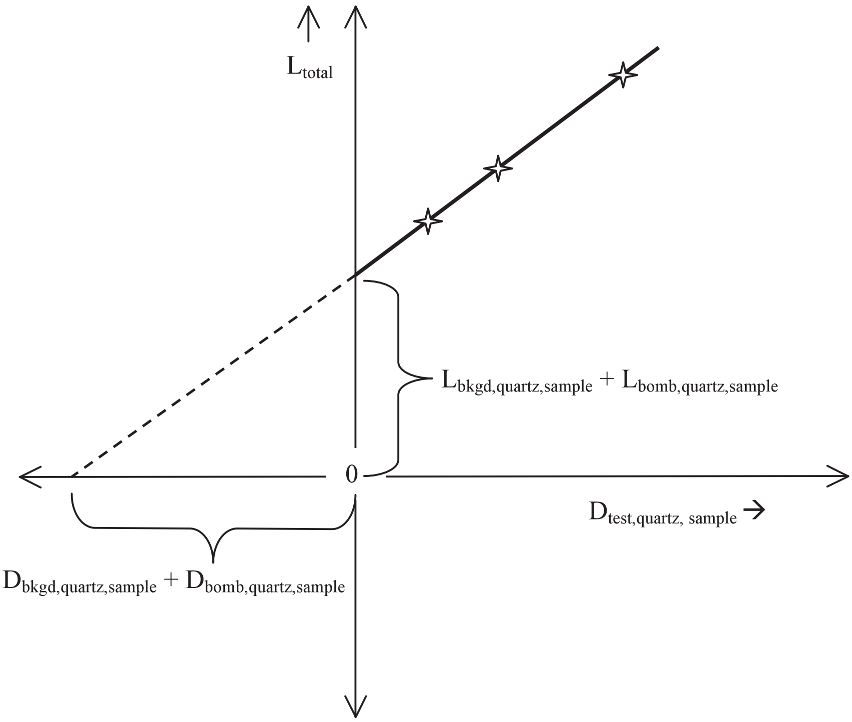

Figure 4. *Concept of test irradiations to calibrate sample-specific TL response. "L" denotes measured light output and "D" denotes dose.*

The fundamental calibration that is performed for TLD measurements uses a gamma or x-ray source and relates most properly to the dose received by the quartz in the sample: "dose to quartz." Because of the dependence of sample response on sample composition, calibrations are performed directly on the samples to be measured, by administering additional radiation doses called "test irradiation" doses to the purified TLD material (separated quartz crystals) from the sample. The test doses, specified as dose to quartz, which we will denote here as $D_{test,quartz,sample}$, above the sum of the doses that the sample quartz received from the bomb ($D_{bomb,quartz,sample}$) and background ($D_{bkgd,quartz,sample}$), are then related to the additional light output that is obtained upon heating the test-irradiated samples, say $L_{test,quartz,sample}$. That is, if various sizes of test doses were administered and response were simply linear over the full range of doses involved, the plot of the total measured luminescence L_{total} vs. $D_{test,quartz,sample}$ would be a line with slope equal to $L_{test,quartz,sample}/ D_{test,quartz,sample}$ and an intercept equal to $L_{bomb,quartz,sample} + L_{bkgd,quartz,sample}$ at $D_{test,quartz,sample} = 0$, as shown in Figure 4. This establishes a sample-specific calibration factor, $L_{test,quartz,sample}/ D_{test,quartz,sample}$ in units such as $Gy_{quartz,sample}$/TL-reader-unit, relating light output and the dose to quartz (right side of Figure 5). The same calibration factor is applied to the light output from the bomb TL sample with no test irradiation dose applied, to obtain an estimate of $D_{bomb,quartz,sample} + D_{bkgd,quartz,sample}$ (bottom left side of Figure 5). This is equivalent to extending the solid line in Figure 4 down to the X-axis, as indicated by the dotted line. $D_{bomb,quartz,sample}$ is then obtained by subtracting $D_{bkgd,quartz,sample}$, which is estimated by other means.

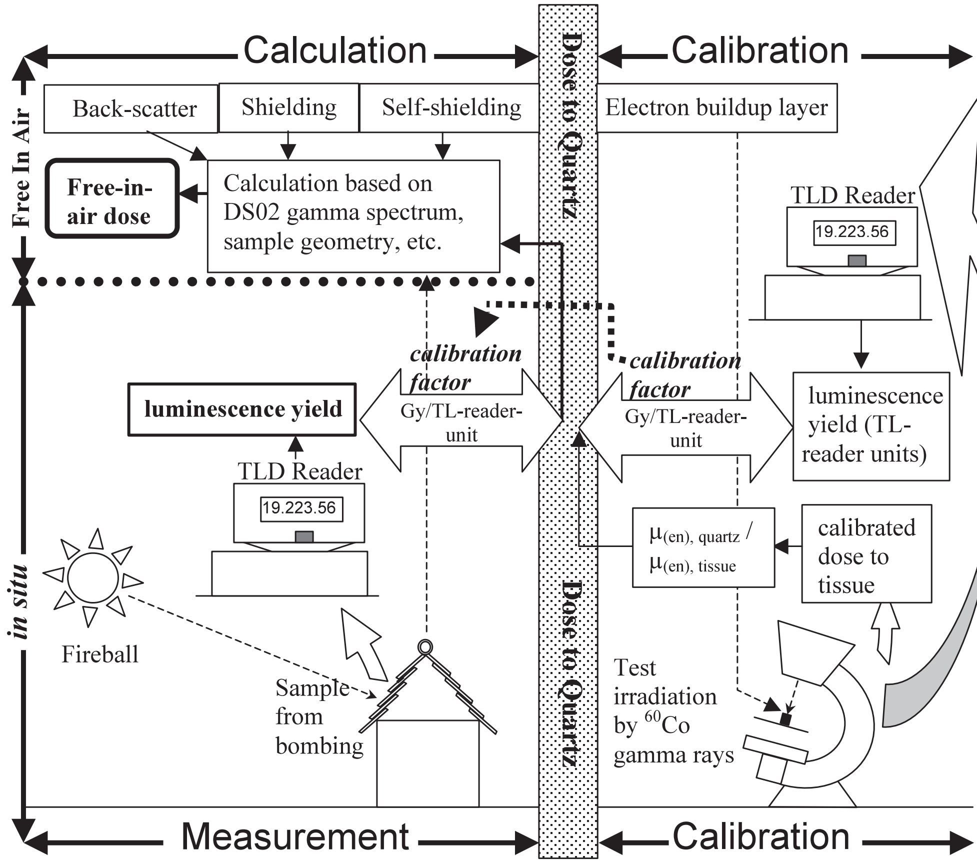

Figure 5. *The relationships among the quantities involved in TLD measurements of bomb-related gamma dose.*

Additional considerations such as correcting for supra-linearity in response are often involved (Maruyama et al. 1987). They do not pertain directly to the present discussion, although they add to uncertainty in their own right. It should also be noted in this discussion that the sample-specific calibration factor, $L_{test,quartz}/D_{test,quartz}$, should not depend on the energy of the gamma or x rays in either the calibration irradiation or the bomb fluence. TL is a broadly sensitive method that accumulates signal proportional to the total amount of energy deposited in the measured material by ionizing radiations, without regard to the type or energy of those radiations. That is, radiations depositing energy in the TL material in quanta sufficient to produce ionization, i.e., above about 8.5 eV, raise electrons from the valence band into the conduction band in numbers proportional to the total energy deposited, and the electron energy transitions involved in TL are transitions of lesser energy related to traps between the energy level of the valence band and the conduction band [Figure 3 and accompanying text in DS86 Final Report, Vol. 1, p. 146 (Maruyama et al. 1987)]. Thus, although there may be a *dose*-dependent *sensitivity* of quartz, where the word "sensitivity" is used to denote the TL signal per unit dose to quartz, for which measurers make corrections (supralinearity correction), and although there is of course an energy dependence of *dose to quartz per unit incident fluence*, there is no basis for an energy dependence of sensitivity, viz., the luminescence per unit dose at a given dose does not depend appreciably on the incident photon energy spectrum producing the dose. Therefore there should be no concern about the energy spectrum of the bomb fluence vs. the test irradiator in regard to the light output per unit average dose to quartz received by the quartz crystals, and this can be excluded from the following analysis.

Various gamma or x-ray sources have been used for test irradiations, but in almost all cases the irradiations were checked and standardized using a ^{60}Co gamma-ray source. Other sources include ^{137}Cs (Maruyama et al. 1987) and Gd x rays produced by excitation using an x-ray machine with a tungsten target (Nagatomo et al. 1988). Additional checks have been done in some cases using higher energy x rays such as those from a 6 MeV accelerator (Hashizume et al. 1967) and an 18.75 MeV accelerator producing 6 MeV effective x-ray energy (Maruyama et al. 1987). Irradiators used to perform test irradiations are usually calibrated in units of dose to tissue at a point in the beam, rather than dose to quartz, and the relationship of $D_{test,quartz,sample}$ to $D_{test,tissue,calibration}$ is established by a standard radiological physics approach based on the mass energy absorption coefficients for the elemental components of quartz and tissue, characterized by effective atomic number, and the beam energies of the irradiator. This completes the picture with respect to determining the dose that was received by the quartz crystals in the sample: energy dependence should not be a significant issue in this regard.

What is of concern in regard to energy dependence is the relationship between the dose to quartz that is measured in the sample and the fundamental quantity of interest to survivor calculations, which is kerma to tissue free-in-air (FIA) at the same location. The dose $D_{bomb,quartz,sample}$ to the *quartz* in the sample is related to the free-in-air kerma to *tissue* that would have been received from the bomb at the sample's location, $K_{bomb,quartz,FIA}$, i.e., at one meter above flat ground with no sample and no sample-containing structure present, by a *transmission factor* (TF). That is, the transmission factor for the sample, $TF_{bomb,sample}$, is equal to $D_{bomb,quartz,sample}/K_{bomb,tissue,FIA}$. This involves a combination of two considerations that were discussed separately above for the test irradiation situation:

1. One is a geometrical consideration related to photon scattering and attenuation at a fairly macroscopic level—to account for the effect of the sample material and surrounding materials, such as shielding by other materials or by overlying portions of the sample material itself, and backscatter from deeper materials (top left side of Figure 5).
2. The other is to account for the energy response of the materials in the sample as it existed *in situ*, at a more microscopic level, which differs considerably from the radiologically idealized situation of the test irradiation, in which the purified quartz material is surrounded by a designed buildup thickness of absorber. In addition to the mass energy absorption coefficients for the elemental components of quartz and tissue and the energies of the bomb gamma fluence, as opposed to the energies of the irradiator beam, there are considerations of electron equilibrium in the intact sample material. This relates particularly to the interface between small quartz crystals and the surrounding matrix of the intact sample, in which they were contained as small and rather sparsely distributed inclusions.

Of these, consideration 1 depends on the energy and angular distribution of the bomb fluence, in addition to the sample geometry, including the depth within the sample of the actual material that was measured, as it existed *in situ* ATB, and consideration 2 depends on the energy and angular distribution of the bomb fluence, as well as on the composition and structure of the sample with respect to the small quartz crystals that are measured and the matrix that surrounded them *in situ*. Because $K_{bomb,quartz,FIA}$ is specified 1 m above flat ground, which is assumed to be level with the hypocenter, the TF must also consider the elevation of ground level at the sample site and the height above ground of the sample location, as explained in Part B of this chapter.

One concern in regard to dose calibration, which applies to results reported prior to DS86, arises from the practice of using a test irradiation source that is calibrated in dose to tissue (or to air, which has a similar effective atomic number) and then quoting the measured TL doses in the same units with no corrections. In fact, some older results are even quoted in Roentgens, which are units of radiation exposure (ionization produced per unit mass of air), for situations in which the irradiators used for test doses were so calibrated. Such a method assumes implicitly, in the case of dose to tissue, for example, that

$$\frac{D_{test,tissue,calibration}}{D_{test,quartz,sample}} = \frac{K_{bomb,tissue,FIA}}{D_{bomb,quartz,sample}} \tag{1}$$

The ratio on the left-hand side of equation (1) is well defined because of the idealized geometry of the calibration setup and the resulting electron equilibrium, but the ratio on the right-hand side is subject to all of the considerations described above in regard to energy dependence and sample *in situ* geometry. Starting with DS86, the ratio of free-in-air dose to the measured *in situ* dose to quartz for a particular sample composition and geometry has been obtained by detailed calculations such as the adjoint Monte Carlo calculations that were performed for Appendix 11 to Chapter 4 of the DS86 Final Report (Kaul et al. 1987). Moreover, DS86 used similar calculations to check this ratio for the calibration setup as well. For example, Appendix 11 to Chapter 4 states on p. 207 that the conversion from roentgens to rad(SiO_2) was determined by modeling the experimental configurations of the calibration facility of each laboratory, including the source, facing material, sample, and backing material.

In DS86, the absorbed dose to quartz for the measured TD samples was based on kerma calculations in a homogeneous sample model for the adjoint Monte Carlo code, and Kaul et al. (1987) note on page 212 of the DS86 Final Report that "The quartz and the surrounding medium were assumed to have the same composition, and electronic equilibrium was assumed in the two." Kerma is the sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing radiation such as gamma rays in a small volume element of a specified material divided by the mass of material in that volume element (Roesch and Attix 1969). It is a useful quantity in dosimetry when charged particle equilibrium exists at the position and in the material of interest, and bremsstrahlung losses by the charged particles are negligible. In this case, kerma and absorbed dose in the material of interest can be equated. Absorbed dose is the energy deposited by charged particles in the small volume element divided by the mass of the specified material within that volume element (Roesch and Attix 1960). The units of absorbed dose and kerma can be either rad or gray. One rad is equal to 100 erg per gram of the specified material, and 1 gray (Gy) is equal to one joule per kilogram of the material (or 100 rad).

Electronic equilibrium may not exist at the boundary of two dissimilar materials (e.g., the quartz crystals in a ceramic tile) (Spiers 1969). The lack of electronic equilibrium involves energy distributions over distances that are less than the range of the photon-produced electrons, and typically, over distances of a few microns to a few hundred microns near the boundary of the two dissimilar materials (e.g., the quartz crystals and ceramic tile). Chemical compositions for ceramic tiles reported by Ichikawa et al. (1966) and Uehara et al. (1988) are summarized in Table 7, and the calculated mass-energy-absorption coefficients (μ_{en}/ρ) for photons in these various ceramic tiles are compared in Figure 6 to that in quartz. The quartz is assumed to be pure silicon dioxide (SiO_2), and the mass-energy-absorption coefficients are taken from Hubbell and Seltzer (2001). The data in Figure 6 show that the energy absorbed from photons in the ceramic tiles is significantly greater than the energy absorbed in the quartz crystals and suggest that electron equilibrium may not exist in the photoelectric interaction region for photons with energies less than several hundred keV.

For the DS02 studies, special Monte Carlo calculations were done using the MCNP computer code and coupled photon-electron transport (Briesmeister 1997). The quartz particles were assumed to be spherical in shape with a diameter of 100 microns. The data summarized in Table 8 show that the sizes of the quartz particles used in the various TLD studies differed somewhat, but a typical size crystal had a diameter of about 100 microns (0.01 cm). In the MCNP calculations, the spherical quartz particles were surrounded by a spherical shell of ceramic tile with an inner radius equal to one-half of the diameter of the quartz particles (50 microns) and an outer diameter equal to 50 microns plus the range of the most energetic electrons produced by a photon (the energy of the most energetic electron would be essentially equal to the energy of the photon). The electron ranges were calculated as a function of electron energy for each of the various tile materials in Table 7 using the ESTAR computer program (Berger et al. 2000). The density of the ceramic materials was assumed to be 1.786 g cm^{-3} (Uehara et al. 1988) and the density of the quartz crystals was assumed to be 2.660 g cm^{-3} (Hodgman 1953).

In the coupled photon-electron calculations with MCNP, the spherical tile shell was irradiated with a plane beam of monoenergetic photons, and the energy deposited in the spherical quartz

Table 7. Literature compositions for ceramic tiles

Element	Percent by weight		
	Hiroshima tile (Ichikawa et al. 1966)	Nagasaki tile (Ichikawa et al. 1966)	Hiroshima tile (Uehara et al. 1988)
H	0.08	0.07	
C	0.15	0.18	
O	47.5	48.2	50.69
Na	0.56	1.21	
Mg	2.44	0.90	
Al	11.8	11.6	11.60
Si	28.4	30.0	34.00
P	0.03	0.07	
K	1.57	1.54	2.55
Ca	1.54	1.32	
Ti	0.31	0.31	
Mn	0.06	0.18	
Fe	5.65	4.38	1.23
Z > 15	9.16	7.80	3.78