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PROBLEMS OF RADIATION DOSE EVALUATION IN HIROSHIMA AND NAGASAKI AND THEIR EXPLANATION

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Abstract — Atomic bomb doses in Hiroshima and Nagasaki have been evaluated by many groups. In the 'Hiroshima Atomic Bomb Dosimetry Group' used in this study, radioactivities of ^{152}Eu and ^{60}Co in exposed rock samples have been measured to evaluate neutron doses both in Hiroshima and Nagasaki. These radioactivities were induced by neutron capture reactions. Thermoluminescence dosimetry has also been applied to estimate gamma ray doses using exposed tile, roof tile and brick samples. After DS86, our group found systematic discrepancies in measured specific radioactivities and calculation based on DS86. The difference, for example, was that measured data were 5 to 10 times larger than the calculation in Hiroshima. The measured gamma ray doses are almost the same as DS86, but they have a similar trend as neutrons, and at 2 km ground range data, are 50–70% larger than the calculation. To find the reason for those problems, some experiments were then carried out by our group. The conclusion of these experiments is that everything seems reasonable except the estimation of neutron and gamma ray spectra at the burst point in Hiroshima. A possible explanation is proposed for the neutron and gamma ray discrepancy in Hiroshima. For this three concepts are assumed as follows: (1) Increase the yield of the atomic bomb about 20%. (2) Leakage of bare fission neutrons from the atomic bomb about 5%, in this model, to the side. That means that for the direction downward, neutrons are shielded with the Hiroshima atomic bomb body. (3) Elevation of burst height about 90 m. By these assumptions all neutron activation data within 1 km ground range and thermoluminescence gamma ray data are simultaneously explained.

INTRODUCTION

Radiation doses for A bomb survivors were established in 1987 in the form of the Dosimetry System 1986 (DS86)[1]. DS86 is the dosimetry system used with epidemiological data for the A bomb survivors at the Radiation Effects Research Foundation and was used to establish new guidelines for radiation safety by the International Commission on Radiation Protection[2] which reflected the increased health risk. Recently the DS86 system was applied to the registry of Hiroshima University[3,4], as well as the analysis of radiation effects using different atomic bomb survivor groups.

However, after the publication of the DS86 report[1], the neutron dosimetry came into question based on further measurements of neutron irradiated samples, including the former data[5–24]. The discrepancy was originally discussed for ^{60}Co activation by Loewe and Mendelssohn[25]. However, at that time, questions were discussed without solutions. There were not enough data to discuss the reason. After the accumulation of data by the above papers, the discrepancy was confirmed. A typical discrepancy is the thermal neutron activation data. The measured data were 2–10 times higher than the DS86 calculations.

The gamma ray doses in Hiroshima are also important because a similar trend of discrepancy is seen[26]. Neutron dose in Hiroshima is relatively small compared with gamma rays. Therefore, it can be said that for the epidemiological analysis, neutron doses are small (sometimes even negligible), and the major portion of radiation is gamma rays. Also, a similar discrepancy for gamma rays implies some relationship with the neutron discrepancy.

After the confirmation of the discrepancy, the study began to solve the reason and to determine the new dose. There were many postulated problems discussed later, such as activation measurements, cross sections used in the transport calculations, air and soil component data used, and so on. Among them, it has been pointed out that there are two major possible causes for this discrepancy. One is an error in the neutron transport calculations including activation from the epicentre to the ground surfaces, and the second is inaccurate neutron source spectrum calculation at the point of detonation.

The first possibility was investigated, for example, by analysing moist air density data in Hiroshima. It was found that the estimated moist air density used in DS86 was accurate enough for the air transport calculations[27]. Further clarification of the first possibility was made using the MCNP transport code system with nuclear data[28]. At first, the accuracy of the code for deep penetration in air-like material was verified by

a 'benchmark test' using a ^{252}Cf fission neutron source. Gold and nickel plates, inserted into moderators including nitrogen, oxygen and hydrogen elements, were activated by thermal and fast neutrons, respectively[29]. Similar experiments were performed using indium, europium and cobalt metal foils as detectors, and 10 cm thick iron to moderate incident neutron energies. Good comparisons were obtained for all of the experiments — the calculated and measured values were within ±40%[30].

Straume *et al*[15,16] obtained specific activity data for ^{36}Cl in Hiroshima by using the accelerator mass spectrometer method. More recently, Straume *et al*[17] obtained specific activity data for ^{36}Cl in Nagasaki and at the Army Pulsed Radiation Facility, and found excellent agreement between the data and the calculation. They concluded from these results that the problem is only in Hiroshima, especially in the output of the Hiroshima atomic bomb. In Nagasaki, ^{152}Eu and ^{60}Co data have been measured but are not yet published. Therefore, in the case of Nagasaki, conclusions should be reached after the confirmation of the ^{152}Eu and ^{60}Co data. In Hiroshima, the problem is believed to be in the output neutrons from the bomb.

Therefore, the second possibility, inaccurate neutron source spectrum calculation at the point of detonation, has been considered by Hoshi *et al*[31]. In that study the MCNP code was used for the analysis, considering source terms and transport calculations using a simple bomb model. A simple shell type atomic bomb model was assumed and Hoshi *et al*[31] tried to explain both thermal neutron activation and fast neutron activation data. Finally they succeeded in simultaneously explaining both factors by using non-uniform leakage of bare fission neutrons. In this study they used a partially opened model and assumed 5% leakage of bare fission neutrons from the opening. In addition to this, they showed that it is necessary to change more of the factors, and if the height of detonation is assumed to be raised about 90 m, then all neutron data will change, at least within 1 km. The data for more than 1 km still has some problems.

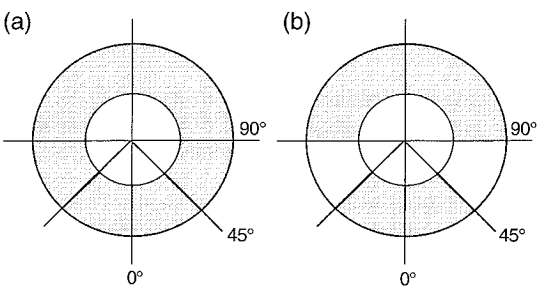

Figure 1. Models used for the calculation of the Hiroshima atomic bomb. (a) Indicates a spherical atomic bomb shell made with 5 cm thick tungsten inside and 20 cm thick iron shell outside. Assuming a fission neutron source at this centre, one can reproduce the DS86 neutron spectrum. (b) Indicates the bare fission neutron leakage model. As seen in this model bare fission neutrons leaked in the direction from 45° to 90°. At first the transport calculations were performed independently for both types. Afterward 95% of the calculated neutron activation or the gamma ray yields of model (a), and 5% yield of model (b) were mixed. In this leakage model about a 90 m increase in burst height was assumed.

Regarding the gamma ray dose in Hiroshima, there is an unknown trend in the discrepancy, and the paper will show how to explain the gamma ray discrepancy. Residual problems of DS86 dosimetry in Hiroshima are also discussed.

MATERIALS AND METHODS

Computer code and input data

The code used was MCNP version 4A, which includes the Monte Carlo source code[28] and the neutron cross-section library as shown in Hoshi *et al*[29] and ENDF version V and VI[28]. For the cross section data of neutron capture gamma rays, Briesmeister[28] was used.

For the bare fission neutron calculation, the Maxwellian distribution of $n(E) = E^{1/2}\exp(-E/T)$ ($T = 1.38$ MeV) as a function of energy E and symmetric point source was assumed. The input data for the neutron transport calculations were taken from the DS86 source term spectrum, assuming spherically symmetric neutron emission and this spectrum was compared with the atomic bomb shell model with 20 cm thick iron and 5 cm thick tungsten inside. Hoshi *et al*[31] show there is no difference between the calculations, at least for the activation calculation.

For the soil components of the ground, data used in DS86[1] was assumed. The moist air density was taken from Hoshi *et al*[27], which was almost equal to the DS86 data.

Geometry of calculation

The neutron energy spectra at the ground surface were calculated using the MCNP code out to 2 km from the hypocentre at 0.1 or 0.2 km increments. The energy division used was the same as that of the DS86 for both neutrons and gamma ray calculations. The total system used for the calculation was a cylindrically symmetric three-dimensional geometry with a ceiling height of 2 km and a ground thickness of 2 m. The burst height was 580 m from the ground surface, which was used for DS86, and a value of 670 m was also used. The results calculated were basically taken within 2 cm thickness in soil from the soil surface for neutron activation. For comparison with DS86 neutrons and for gamma ray dose, those at 1 m in height were obtained. The calculation within 2 cm in soil was chosen to compare with the activation data of ^{152}Eu, ^{32}P, ^{60}Co and

^{36}Cl, since the measured data were obtained from the surface to 2 cm thickness of the specimens. Calculated points were regarded as between the interval of increments (i.e. 50, 150, 250 m, etc.).

Cross section for yield calculation

The neutron fluences calculated within soils (cells) or surfaces were multiplied by the cross sections of $^{151}Eu(n,\gamma)^{152}Eu$ (Hasai *et al*[5]), $^{32}S(n,p)^{32}P$, $^{59}Co(n,\gamma)^{60}Co$ and $^{35}Cl(n,\gamma)^{36}Cl$. The sulphur reaction cross sections were obtained from the table of McLane *et al*[32]. The reaction cross section of cobalt was taken from JENDL-3[33] and that of chlorine was obtained based on ENDF-IV, except for the thermal neutrons. For the thermal neutron reaction cross section of chlorine, 41.80 b was used[32]. For the calculation of the air kerma of neutron data, Standard Man in the table of Howerton[34] was used. For gamma ray kerma calculation, energy absorption coefficients of 'Adult #2 data' from the International Commission on Radiation Units and Measurements Report 46 data[35] were used.

Data used for neutrons

Activity data for ^{152}Eu which was induced by the Hiroshima atomic bomb neutrons used for the analysis were taken from Shizuma *et al*[9,10,12], Nakanishi *et al*[13,14] and Hoshi *et al*[6–8]. Those for ^{60}Co were from Shizuma *et al*[9–11], Kerr *et al*[24], Hoshi and Kato[6] and

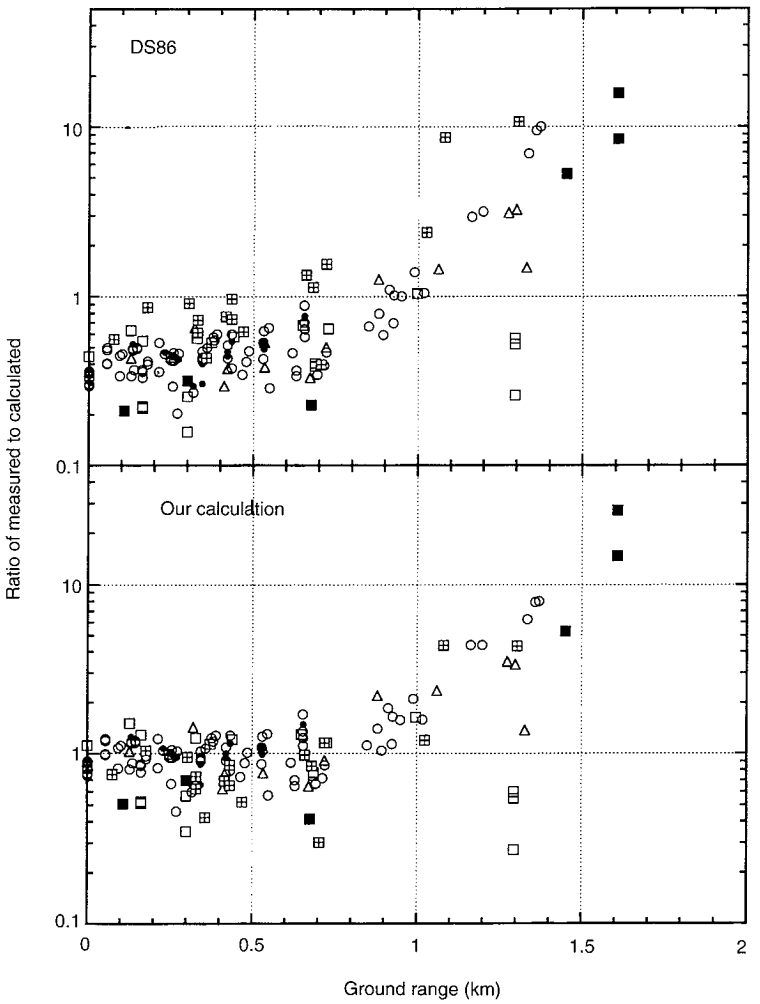

Figure 2. Measured data and calculations for neutron activation are compared in this figure. The upper half shows the ratio between measurements and calculation based on DS86 for comparison. The lower half compares measurements and our leakage model (Figure 1) as in the upper one. Within 1 km ground range adjustment was achieved; however, at more than 1 km ground range, there is residual discrepancy. Data from: (○) Ref. 10, (△) Ref. 14, (●) Ref. 8, (□) ^{60}Co, (⊞) ^{32}P, (■) ^{36}Cl, Ref. 16.

Hashizume *et al*[23]. The data on chlorine activity were from Straume *et al*[15–17] and Kato *et al*[36]. The yield of ^{32}P was originally measured by Yamasaki and Sugimoto[19], and Arakatsu *et al*[18]. Hamada[22] re-evaluated Yamasaki and Sugimoto[19] data, and Shimizu and Saigusa[21] also re-evaluated Arakatsu[18] data. In this study, these re-evaluated data, which is cited in Gritzner and Woolson[37], were used for the analysis.

Data used for gamma rays

Gamma ray data are obtained by the thermoluminescence dosimetry method. Specimens used are atomic bomb exposed tiles, roof tiles and bricks. Data used are taken from Hashizume *et al*[23], Haskell *et al*[44], Hoshi *et al*[40], Ichikawa *et al*[38,39,45], Maruyama *et al*[46] and Nagatomo *et al*[26,41–43].

RESULTS AND DISCUSSION

The model used for the calculation

Figure 1 shows a simple model of an atomic bomb. Figure 1(a) shows a simple shell type model, which can reproduce the DS86 source spectrum, Figure 2(b) shows an open model. As seen in Figure 1(b), an opening from 45° to 90° was assumed. Hoshi *et al*[31] made transport calculations and obtained the neutron activation yield. In this paper, neutron capture gamma ray yield was calculated using this model. For the calculation of DS86, Figure 1(a) was used with the same fluence as DS86. In the case of the leakage model, from something like the 'space of the crack', a similar calculation was made for both models. Then 95% of Figure 1(a) and 5% of Figure 1(b) calculations were added. In this model it was necessary to raise the burst height about 90 m.

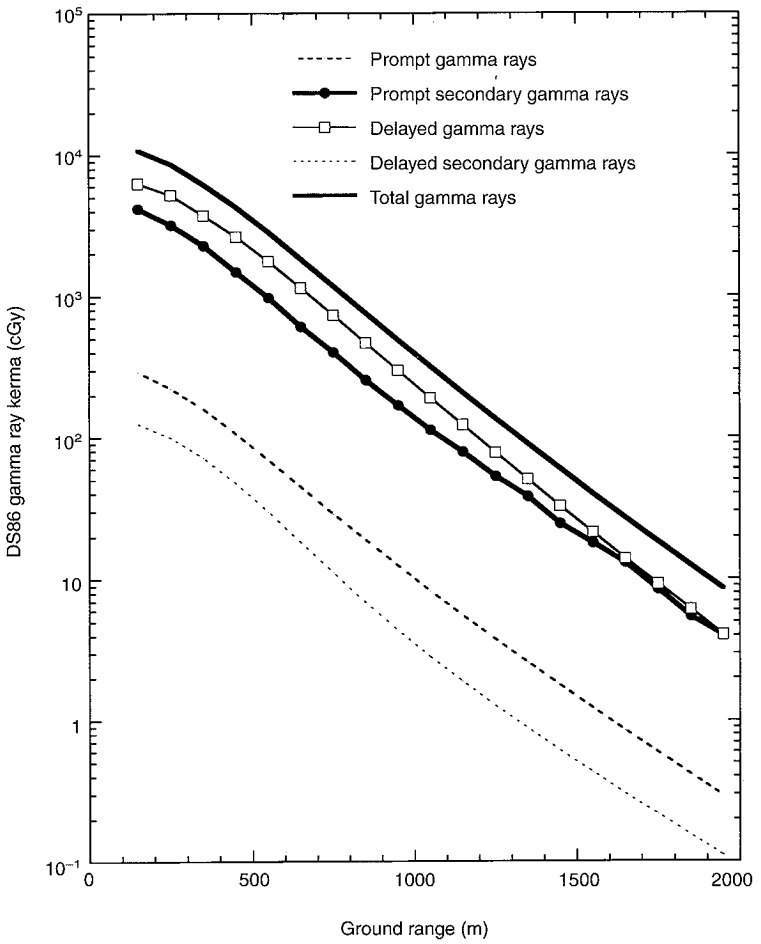

Figure 3. Components of gamma rays of DS86[1] are shown. Major components are 'delayed gamma rays' and 'prompt secondary gamma rays' as shown here. Prompt gamma rays and delayed secondary gamma rays are less than 10% of the major components.

Therefore this model assumes (1) 5 % leakage of the opening from 45° to 90°, and (2) increase of height of burst by 90 m. According to this model, the measured data and calculation agree well within 1 km of the ground range (Figure 2). It should be noted that in Figure 2, there are two types of neutron activation data. One is due to thermal neutrons (^{60}Co, ^{152}Eu, ^{36}Cl): the other is due to fast neutrons (^{32}P).

However, long range data for more than 1 km still have discrepancies. The reason is unknown and is a difficult problem. Because if this curve is explained by changing only the source term energy, one must assume a neutron energy more than 8 MeV. This seems impossible, since original fission neutrons do not have such an energy as a major part.

Component of gamma rays

The gamma ray component in DS86[1] is shown in Figure 3. In Figure 3 four components are shown. They are (1) delayed gamma rays, (2) prompt secondary gamma rays, (3) prompt gamma rays, and (4) delayed secondary gamma rays. Prompt gamma rays are emitted at the moment of fission and, after this, delayed gamma rays are from the fire ball and the mushroom cloud. Secondary gamma rays are induced gamma rays by neutrons according to the interactions with air, soil and Japanese house components. Delayed and prompt gamma rays are induced from the delayed and prompt neutrons. From this figure, it is shown that the major ones are both the delayed and prompt secondary gamma rays.

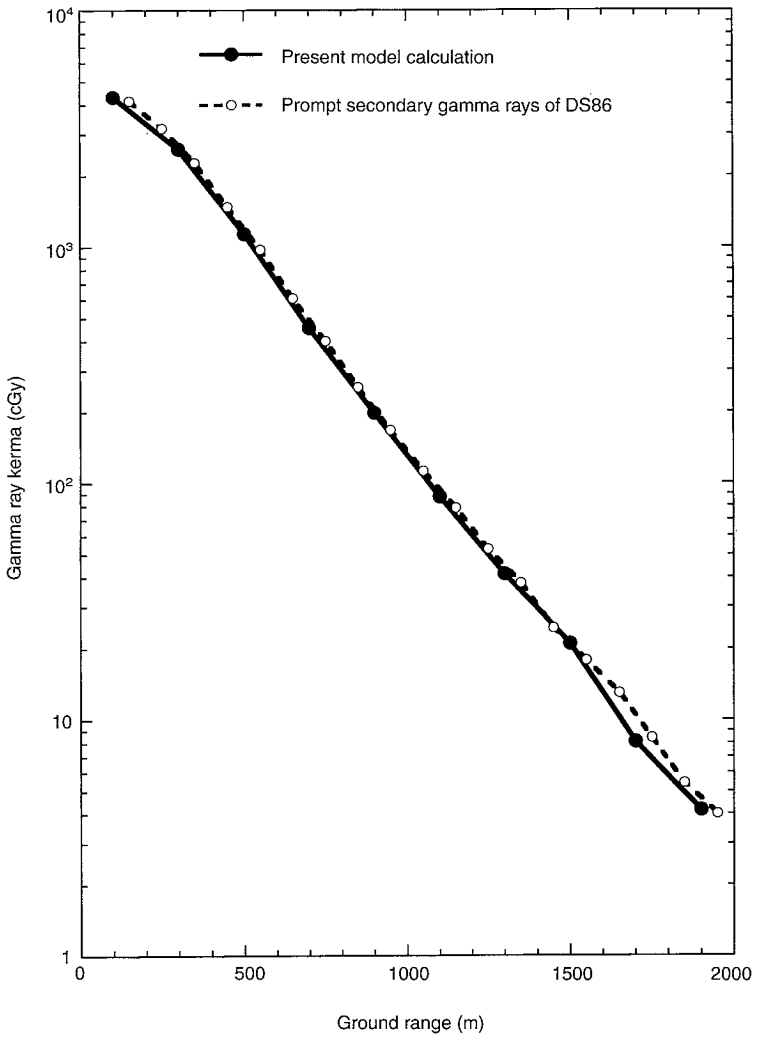

Figure 4. Our model calculation (—●—) for the prompt secondary gamma rays at the condition of DS86 is tested to compare with DS86 itself (– –○– –). Gamma ray kerma was calculated and, as seen in this figure, it is shown that our model calculation agreed well with DS86.

In this paper the components of prompt secondary gamma ray yield are obtained after the prompt neutron transport calculation.

Comparison between DS86 and model calculation

Figure 4 compares prompt secondary gamma rays of DS86 and presents calculations using the simple shell model indicated in Figure 1 (a). The two curves agree with each other. This model calculation was for used bare fission neutron leakage model of Figure 1 (b).

In this paper, only the model calculation for prompt secondary gamma rays was made. One reason is that the other major components of delayed gamma rays come from the fire ball and the mushroom cloud, therefore there are limits to getting precise information to perform this calculation. The use of DS86 delayed gamma rays corresponds to the use of the same burst height as DS86. When we think the burst height is determined by the shadow of the fireball, and that delayed gamma rays are coming from the fire ball and the mushroom cloud, the emission point is considered to be the same.

On the other hand, the use of the 'crack model' means

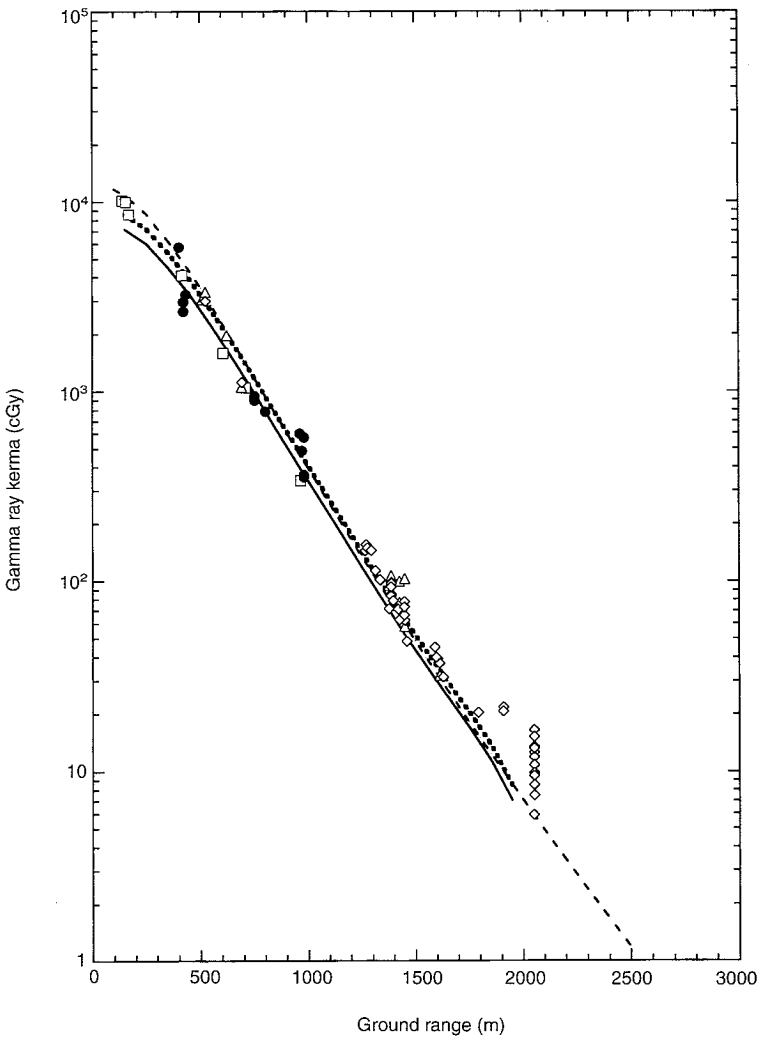

Figure 5. The measured data and calculations for gamma rays are compared. Total gamma rays of DS86 is indicated by the light dashed curve and that from our model calculation (5% leakage and 90 m elevation of burst height) is shown by the narrow solid curve. Slope of the latter (the narrow solid curve) seems to be close to the data: however, it is low as a whole. To adjust this, gamma ray dose was increased by 20% as shown by the heavy dashed curve. This curve seems best, comparing the three calculations. Other points: (□) Hashizume 1967[47], (●) Ichikawa *et al* 1966[38], (△) Maruyama *et al* 1988[46], (◇) Accumulated data of the Ichikawa group[26,39–43,45].

elevating its height about 90 m. Therefore, to use this model for prompt secondary gamma rays and DS86 for delayed gamma rays, means the use of different burst heights. Of course, it is not verified, but this corresponds with the fall of 90 m due to the time duration between the emission of prompt neutrons and delayed gamma rays. The discussion of the difference, or calculation of delayed gamma rays, should be made at another time, since we do not have enough information.

Comparison with gamma ray data

In Figure 5, all thermoluminescence data and calculations are compared. The data are obtained from the thermoluminescence dosimetry measurement by using atomic-bomb irradiated tile, roof tile and brick specimens. The light dashed curve is DS86 gamma rays and the narrow solid line is the curve when the burst height of prompt secondary gamma rays is raised 90 m. The latter is obtained from the calculation which shows better fitting within 1 km as in Figure 2.

However, this narrow solid line seems a little bit lower than the data, while the slope seems to fit better than DS86. When a better fit is chosen for the slope then the dose must be increased. The heavy dashed curve is obtained by increasing the dose for the narrow solid curve by 20%. This means increasing the yield at the burst by 20%.

As shown in Figure 5, the thick dotted curve fits better than the other two. Note that there are some higher data at 2 km ground range for all of these calculations.

The conclusion is that when we assume (1) increment about 20% of yield, (2) 5% leakage of bare fission neutrons from the space of the atomic bomb, and (3) 90 m increase of the burst height, we have the best fit. This assumption is listed in Table 1. Thus the best fit for gamma rays in Hiroshima is as shown in Figure 5. The overall best fit, including neutrons, should be precisely considered after the solution of the long-standing systematic discrepancy. In this paper a basic possible concept to explain the tendency of the discrepancy in Hiroshima gamma rays is discussed. For the final solution of Hiroshima atomic bomb dosimetry, it is necessary to discuss both neutrons and gamma rays simultaneously.

ACKNOWLEDGEMENTS

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Table 1. Basic assumption for our bare fission neutron leakage model.

Item	Increment
Yield	+20%
Fast neutron leakage in this model	+5%
Burst height	+90 m

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