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There has been a large discrepancy between the Dosimetry system 1986 (DS86)¹⁾ and measured data, some of which data in Hiroshima at about 1.5 km ground distance from the hypocenter are about 10 times larger than the calculation. Therefore its causes have long been discussed^{2–10)}, since it will change the estimated radiation risks obtained based on the Hiroshima and Nagasaki data. In this study the contradiction was explained by a bare-fission-neutron leakage model through a crack formed at the time of neutron emission. According to the present calculation, the crack has a 3 cm parallel spacing, which is symmetric with respect to the polar axis from the hypocenter to the epicenter of the atomic bomb. We made also an asymmetric opening closing 3/4 of this symmetric geometry, because there are some data which shows asymmetry^{5,12,13)}. In addition, the height of the neutron emission point was elevated 90 m. By using the asymmetric calculation, especially for long distant data located more than 1 km, it was verified that all of the activity data induced by thermal and fast neutrons, were simultaneously explained within the data scattering. The neutron kerma at a typical 1.5 km ground distance increases 3 and 8 times more than DS86 based on the symmetric and asymmetric model, respectively.

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INTRODUCTION

In 1986, "Dosimetry system 1986 (DS86)", which estimated radiation doses for the atomic-bomb survivors in Hiroshima and Nagasaki, was established according to the project of the US-Japan joint study¹⁾. The DS86 has been used for the radiation risk estimation by using the epidemiological data such as cancer induction for atomic bomb survivors at Radiation Effects Research Foundation. Almost all of the radiation risk data are obtained based on its study and recommended at the International Commission on Radiation Protection in 1990¹⁴⁾. Those are used to estimate risks of radiation for workers and general people who are in factories, institutions hospitals and so on.

However the thermal-neutron-induced activity data, such as the specific activities of ^{152}Eu , ^{60}Co , ^{36}Cl , measured after this project, showed discrepancy from the estimation based on DS86²⁻¹¹⁾. The data were about half at short distances and agree with the DS86 calculation at about 800 to 1000 m. From 1000 m, data come up very higher, for example, at most about 10 times higher than DS86 calculation as shown in Fig. 2 and in the upper figure of Fig. 3.

There are the other activity data^{15,16)} of ^{32}P , which was induced by fast neutrons (>1.6 MeV) also showed similar discrepancy as those induced by thermal neutrons³⁾. The ^{32}P data are important because neutron doses for atomic bomb survivors were given by such fast neutrons.

Based on above mentioned data there have been many discussions for this question. At first the measured data have been questioned such as (1) whether there were backgrounds in the measurements of ^{152}Eu or ^{60}Co , (2) neutrons from the other sources, such as, cosmic rays, and (3) problems for long distance samples in the process of the chemical enrichment. However we have not found any problems for them.

Secondly, (4) data used in the DS86 was checked such as used air density data including humidity was evaluated based on actual measurement¹⁷⁾, however there were no problems for such data. (5) Then the problem for the neutron transport calculation after they were released from the Hiroshima atomic bomb was considered. Benchmark tests have been performed^{18,19)} using a ^{252}Cf fission neutron source. The neutrons were transmitted through moderators (Lucite, water, Nylon, ammonium chloride, polyethylene with boron), which have total thickness of 65 cm. The thickness corresponds to the ground distance about 1.5 km. Activation foils of gold, indium, nickel, europium, cobalt were used to detect thermal neutrons and fast neutrons, and were compared with the calculation by the Monte Carlo N-Particle Transport Code System (MCNP 4A)²⁰⁾ calculation. All of these calculated results agreed within the experimental errors about 30%.

There are the other discussions for this verification of the transport calculation. It is to compare its discrepancy from Nagasaki. Only difference between two cities is in the source terms of the two bombs. If there are no discrepancy in the case of Nagasaki, then the problem is verified to be in the source term of the Hiroshima atomic bomb. Straume et al²¹⁾ measured ^{36}Cl and showed that its data and calculation based on DS86 agree each other. Recently, Nakanishi et al²²⁾ published ^{152}Eu data, which seems to agree with DS86. So far, it is considered to be its problem is in the neutron source term in Hiroshima, however, it will be necessary to confirm

more the Nagasaki data.

The source term of Hiroshima atomic bomb was obtained in DS86 according to the precise calculation by Whalen²³⁾. The Hiroshima type bomb was called as gun type, in which two sub-critical enriched ^{235}U was brought together at the head of the bomb and exploded. One of the difficulties is that all of the atomic bombs ever used have been an implosion type. The bomb body was made with thick steel and DS86 assumes that induced fission neutrons were emitted before the bomb body was exploded. The neutrons from Hiroshima atomic bomb in DS86 interacted with iron and lost their energy according to the inelastic scattering of the $\text{Fe}(n, n')$ reaction. Therefore the neutrons were attenuated more rapidly than the bare fission neutrons.

At more than 1 km the discrepancy increases very large. It seems we need the other mechanism of an emission model. Among such considerations, a pancake type emission model was proposed²⁴⁾, which means emission only for the horizontal direction from the bomb. However it concluded this type of emission is not plausible since no neutrons emitted to the direction for its bottom. As one of the considerations, fast neutron leakage model was tested²⁵⁾. In this model, bare fission neutrons leaked through a crack and succeeded in the explanation within about 900 m ground range. However, it assumed relatively a large opening, therefore, only 5% of the total neutron emission can be added to the closed or DS86 calculation. It is difficult to consider the possibility that the crack was formed within the time of fission chain reaction about 1 microsecond. Also, it cannot produce difference caused by an asymmetric emission and, consequently, it cannot solve the large discrepancy more than 1 km.

MATERIALS AND METHODS

In the present study, it is assumed to use¹⁾ already (1) known fission neutron spectrum, (2) known outline of the Hiroshima bomb geometry, (3) known air component and (4) known soil component. Using these factors, thermal- and first- neutron activation data have been tried to fit simultaneously. Finally, we found a solution using a narrow 3-cm parallel opening, which is symmetric with respect to the polar axis from the hypocenter to the epicenter, as shown in Fig. 1 (a). The outer size of the bomb are shown in Fig. 1²³⁾. The distance from the bomb head to the fission point was taken to be thick. It was essential because it caused heavy shielding to the ground range area. The structure of the Hiroshima atomic bomb is still classified. Therefore it is not clearly known for us, but there is a possibility that the other element such as tungsten was used as tamper which reflect neutrons inside. We calculated the effect, however, it does not essentially change the activity yields, if we adjust the total neutron fluence outside of the bomb equal to DS86. The radius of the uranium was assumed from the used total uranium of 42 kg²⁶⁾, which correspond to the sphere with the radius of 8.1 cm. We also assumed the height of neutron emission of 670 m, which is 90 m higher than that of DS86. Using the bomb geometry as shown in Fig. 1, neutron-transport calculations through air were performed and neutron fluence spectra in the 2-cm-surface soil disk and so on were obtained. The geometry of the calculation was taken to be the same as the reference²⁵⁾.

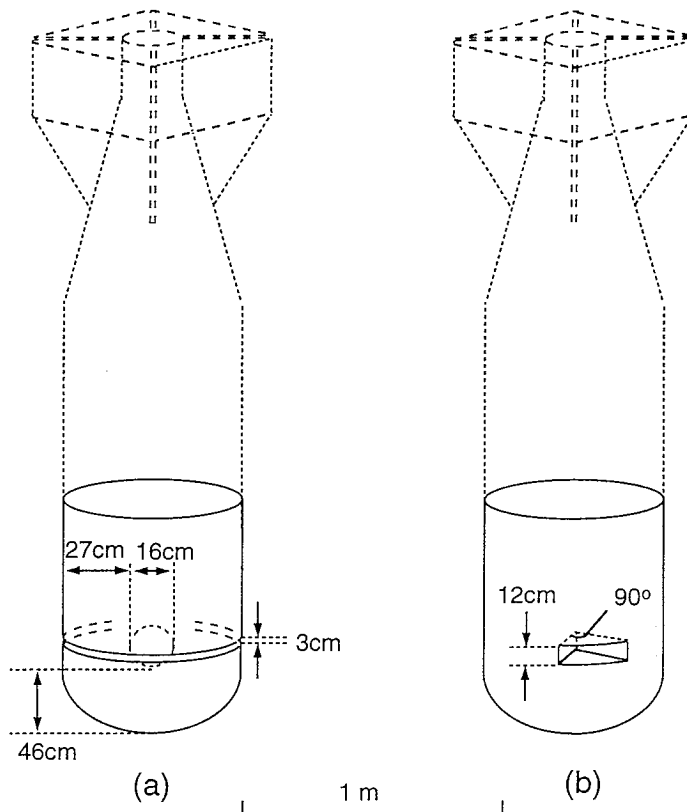


Fig. 1. Crack model of the Hiroshima atomic bomb used for the calculation. In (a) the symmetric opening is shown. The opening has the narrow 3-cm parallel gap which is symmetric with respect to the polar axis from the hypocenter to the direction of the epicenter of the Hiroshima atomic bomb. From here it is noted as the polar axis. In (b) the asymmetric 90° opening is indicated. To adjust the total area of the opening to be the same, the gap is taken to be 12 cm. For the element of the bomb body, only iron was assumed. Since the structure of the Hiroshima atomic bomb is classified. There is a possibility that the other element such as tungsten was used as tamper which reflect neutrons inside. However, the present calculation using iron without tungsten do not essentially change the conclusion, which is written in the text.

RESULTS AND DISCUSSION

Figure 2 shows the comparison of present calculation with the activity data of ^{152}Eu , ^{60}Co , ^{32}P and ^{36}Cl . The present calculation shows better agreement for thermal neutron activation and first neutron activation data at relatively long distant place. The spacing was changed from 2 cm to 10 cm to test the difference. From the comparison between the fast neutron and thermal neutron yield, 2- or 3-cm spacing seemed to give the best fit. Here, we use 3-cm spacing. In addition, different types of openings were tested such as taper openings, or parallel and slant

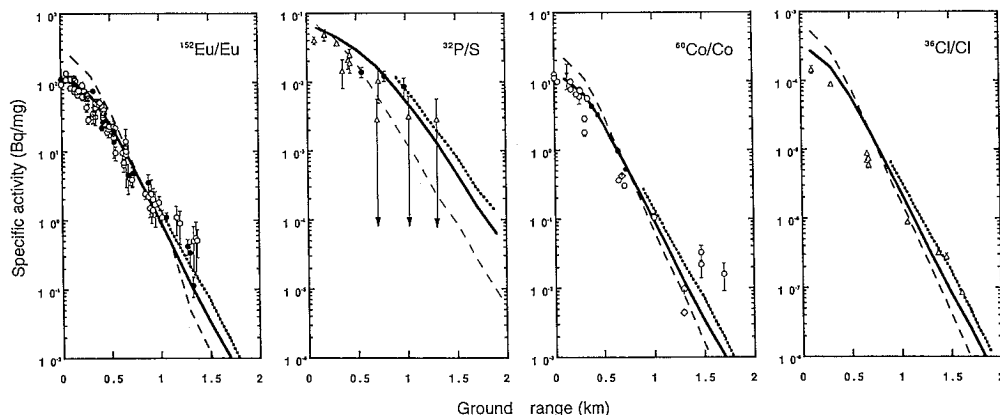


Fig. 2. Comparison of the present calculation with the four types of the neutron-induced activity data. The europium data ($^{152}\text{Eu}/\text{Eu}$) are taken from the Hiroshima group²⁻⁵⁾ (\circ) and Nakanishi et al²²⁾ (\bullet). For the calculation of the thermal neutron activation, neutron fluences in the 2-cm-surface soil disk were used. The sulfur activation data ($^{32}\text{P}/\text{S}$) are taken from Arakatsu et al¹⁵⁾ (\bullet) and Hamada's reevaluation¹⁵⁾ (\triangle). For the calculation of the sulfur activation, neutron fluences at about 10 m height were used and the effect of the porcelain insulator shielding¹⁾, in which sulfur was included, was calculated. The three arrows at the error bars indicate the ends of the lower error limits are going down to zero. The cobalt activation data ($^{60}\text{Co}/\text{Co}$) are taken from Hiroshima group²⁻⁶⁾ (\circ), Hashizume et al⁷⁾ (\bullet), Kerr et al⁸⁾ (\diamond), Nakanishi et al¹⁾ (\blacktriangledown) and Kimura et al⁹⁾ (+). The data of ^{60}Co at about 1.4 km ground range are those from the Yokogawa bridge. The sampling point of the Yokogawa bridge is about 11 m higher than the ground level, therefore 60% decrease of the yields from the ground surface were corrected. The ^{36}Cl data ($^{36}\text{Cl}/\text{Cl}$) are taken from Straume et al¹⁰⁾ (\triangle). The present symmetric calculations are shown by solid lines whereas the lower dashed lines indicate DS86. The results of the asymmetric emission are indicated by dotted lines more than about 1 km ground range. For the yield calculation energy bin of the thermal neutron was taken to be the same as DS86, which has only one energy bin. In the present calculation errors occurring due to this large energy bin, were corrected for all of the thermal neutron activation based on the precise MCNP calculation. The correction factors, which decrease calculated yields, are 0.72, 0.80 and 0.83 for $^{152}\text{Eu}/\text{Eu}$, $^{60}\text{Co}/\text{Co}$ and $^{36}\text{Cl}/\text{Cl}$, respectively. The total released energy from the Hiroshima atomic bomb was increased 20%, as discussed in the reference²⁷⁾. This is because the gamma-ray yields according to the neutron-capture reaction do not change whether neutrons were emitted through iron or through crack. The symmetric calculation shows better agreement than the DS86 for thermal neutron activation and first neutron activation data at relatively long distant places. Within 1 km, the symmetric model agrees with the experimental data within the data scattering. At more than 1 km ground range, asymmetric calculation gives higher values and seems to give better fit. For the case of cobalt activation, relatively large data scattering are observed. Directions of the almost all data more than 1 km are located between for the south and for the east.

openings. Even if we assume such openings, we had essentially the same result as the parallel openings. Larger openings increase the yield of the ground range area more sensitively for fast neutron reaction data of ^{32}P than for the thermal neutron data. In addition to symmetric model asymmetric calculation was made and shown in Fig. 1 by dashed lines. By using this calculation better fits at more than 1 km ground range were obtained.

About the crack formation, we should consider its possibility. It is known that the chain reaction must be finished within an order of one microsecond²⁸⁾ while for the formation of the

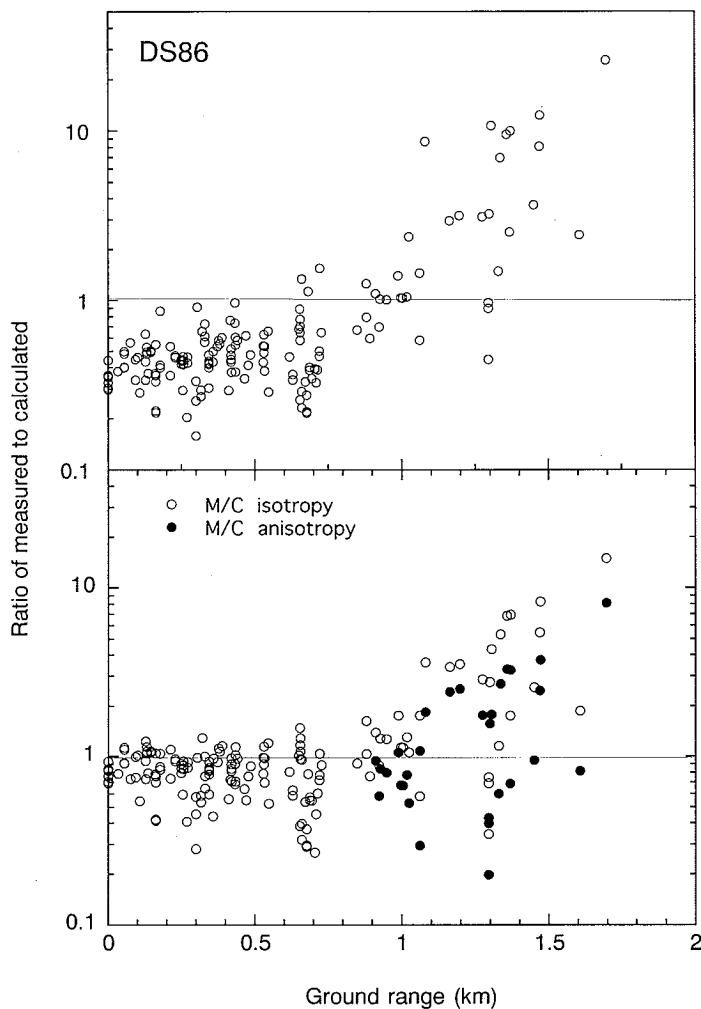


Fig. 3. Ratios of the measured to calculated activity yields are shown. Upper figure shows comparison with DS86 and lower one does with the present calculation. If the calculation and data agreed with each other, the plots should scatter around the value of one. The upper figure, which compare with DS86, shows lower values than unity at short distances and, from more than 1 km, data seems to increase up to very high level. The open circles in the present calculation are based on the symmetric calculation. While closed circles more than 0.9 km ground distance indicates those based on the asymmetric calculation of which data are in the direction between to the south and to the east. Five open circles more than 0.9 km ground range are located almost in the direction to the north. The correction less than 0.9 km ground range was not made. For asymmetric calculation it lowers the data points within 30% for thermal neutron and within 46% for fast neutron activation, respectively. The lower figure indicates that the present calculation is reasonably reproduced the data within data scattering.

crack an order of one millisecond should be needed. However, it was reported about 3% of uranium was burned out and 97% was left without fission²⁶⁾, therefore the chain reaction must be stopped when it lost the criticality. It may be due to the increase of the volume, therefore we must know the mechanism of the volume increment within a order of a few to several microsecond or longer reaction period to enlarge the volume. Or there may be a process of the crack formation begun before the chain reaction started.

The elevation of height was incorporated because the ^{32}P yields were almost agreed with DS86 and that the assumption of the fast-neutron leakage increases not only for ^{32}P but also thermal neutron reaction yield. It is necessary to include the factor to reduce the ^{32}P yield calculation near ground zero. The elevation of the height reduces the yield near hypocenter but not for larger distant activation. There is some directly observed record of the Hiroshima atomic bomb explosion that showed two times flushes of the Hiroshima atomic bomb. For example Uda et al²⁹⁾ noted time between two flushes is the order of 0.5 second. Endo et al³⁰⁾ estimated time between the two flushes to be from 0.1 to 0.5 second based on the direct observation and calculated the difference of the height correspond to 40 to 200 m using the estimated speed at the epicenter from

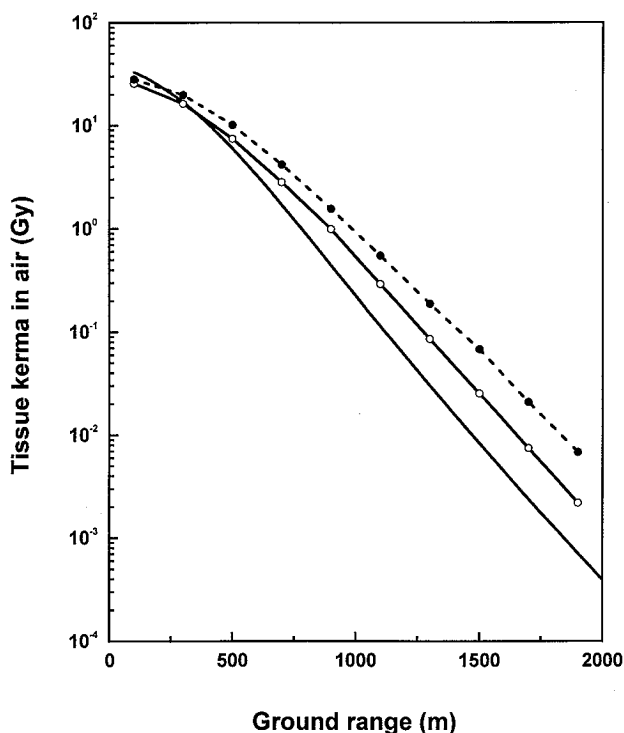


Fig. 4. Tissue kerma in air are obtained from the neutron spectra at 1-m ground surface. Within 1-km ground range, there are not many survivors since this area was very heavily destroyed and, more than 2-km ground range, doses for the survivors are low. Therefore typical ground range is between 1 km and 2 km. At 1.5 km, the present calculation is 3 and 8 times higher than DS86 (solid line) for symmetric (solid line with open circles) and asymmetric calculation (dotted line with closed circles), respectively.

380 to 400 m/s. From these information 90 m elevation seems to be within reasonable range.

In Fig. 2, results of the asymmetric emission are indicated by dashed lines. There are three published data, which shows asymmetric yields. (1) Radiation from the hypocenter area within about 500 m was measured immediately after the bombing and found asymmetry to the directions of southwest and east¹². (2) There was a trend of the anisotropy for ¹⁵²Eu activation to the southeast direction⁵. (3) Difference of the cancer mortality was found to the direction for west southwest¹³. Although these directions are not agree each other, it may be coming from the difference of neutron energy or from more than two openings. However it can be noted that such asymmetry will be considered by crack formation. In Fig. 3 comparisons of the data with DS86 and the present study are shown. The open circles in the lower figure indicates comparison based on symmetric calculation. The closed circles indicates correction by using the asymmetry calculation, directions of which data are taken between those located to the south and to the east.

In Fig. 4 tissue kerma in air was calculated. The kerma is 3 times higher at the typical point of 1.5 km and 8 times, respectively for symmetry and asymmetry calculation.

CONCLUSION

In this study, the new neutron emission model was presented. To explain the measured data, neutron emission according to the concepts of (1) heavy shielding to the direction for the hypocenter (46 cm thickness), (2) strong horizontal collimation which corresponds to 3 cm parallel spacing, and (3) elevation of the neutron emission point about 90 m. In addition, (4) the yield of the Hiroshima atomic bomb was increased 20%²⁷. According to the model presented here, discrepancy from thermal and fast neutron activation data of ¹⁵²Eu, ⁶⁰Co, ³⁶Cl and ³²P was explained simultaneously. Not only the parameters noted here such as the spacing of the crack, the change of height, increment of the bomb yield, but also the total dosimetry system for each survivor and for each organ should be precisely reevaluated to obtain final dose evaluation system for the atomic bomb survivors. The epidemiological data in Hiroshima and Nagasaki should be also reevaluated based on the newly estimated doses. It is to know true radiation risks for people.

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