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DEVELOPMENT OF A-BOMB SURVIVOR DOSIMETRY*

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Abstract

An all important datum in risk assessment is the radiation dose to individual survivors of the bombings in Hiroshima and Nagasaki. The first set of dose estimates for survivors was based on a dosimetry system developed in 1957 by the Oak Ridge National Laboratory (ORNL). These Tentative 1957 Doses (T57D) were later replaced by a more extensive and refined set of Tentative 1965 Doses (T65D). The T65D system of dose estimation for survivors was also developed at ORNL and served as a basis for risk assessment throughout the 1970s.

In the late 1970s, it was suggested that there were serious inadequacies with the T65D system, and these inadequacies were the topic of discussion at two symposia held in 1981. In early 1983, joint U.S.-Japan research programs were established to conduct a thorough review of all aspects of the radiation dosimetry for the Hiroshima and Nagasaki A-bomb survivors. A number of important contributions to this review were made by ORNL staff members. The review was completed in 1986 and a new Dosimetry System 1986 (DS86) was adopted for use.

This paper discusses the development of the various systems of A-bomb survivor dosimetry, and the status of the current DS86 system as it is being applied in the medical follow-up studies of the A-bomb survivors and their offspring.

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1. Introduction

Two important parameters in the radiation dosimetry for individual A-bomb survivors are distance and shielding (Noble, 1967). For example, some individuals survived very close to the bombs because they were shielded by buildings or terrain (see Fig. 1). Other individuals survived because they were located at very large distances from the hypocenters of the bombs. Thus, distance from the hypocenter or ground range was one of the criteria used in the selection of the major study populations of the Radiation Effects Research Foundation (RERF) and its predecessor, the Atomic Bomb Casualty Commission (ABCC) (Beebe and Usagawa, 1968).

A summary of the major study populations is provided in Table 1. The survivors (and offspring of survivors) who were located at ground ranges of less than 2500 m are the core group of the major study samples and are often referred to as the proximal exposed group. Other groups used as controls are the distal exposed group of survivors who were located at ground ranges between 2500 and 10,000 m, and the not-exposed group of survivors who were located at more than 10,000 m. The not-exposed group is referred to commonly as the not-in-city (NIC) group because it contains a large number of individuals who were not in the cities at the time of bombing (ATB) but took up residency in Hiroshima or Nagasaki prior to 1950 (Ishida and Beebe, 1959).

Shielding histories were compiled for proximal exposed survivors starting in 1951 in Nagasaki and 1954 in Hiroshima (Noble, 1967; Beebe and Usagawa, 1968). The strategies used in the two cites were somewhat different because there were more proximal exposed survivors in Hiroshima than in Nagasaki (see Table 2). In Nagasaki, shielding histories were compiled on all survivors who were located at ground ranges of less than 2000 m. However, the approach in Hiroshima was to take shielding histories out to 2000 m for only those survivors included in smaller study samples such as the Adult Health Study (AHS) and *In utero* Mortality Sample. It was decided initially that shielding histories would only be taken on the Life Span Study (LSS) subjects who were located at less than 1200 m. After shielding histories were compiled on the LSS subjects under 1200 m, however, the 100 percent criteria was extended to those LSS subjects under 1300 m, and so on, ending at 1600 m (Milton and Shohoji, 1968).

When the T65D system became available (Auxier et al., 1966), it appeared that the radiation doses were approximately equal at 1600 m in Hiroshima and 2000 m in Nagasaki. At that time, shielding histories were available for most of the Nagasaki survivors who were located at ground ranges of less than 2000 m. In Hiroshima, shielding histories were available for most of the LSS subjects under 1600 m, 30% of the LSS subjects between 1600 and 2000 m, and most other sample subjects under 2000 m. In both cities, there were a number of cases in which shielding histories were either incomplete or unavailable because of the migration or death of survivors before 1965. For some cases, however, information such as "exposed inside a Japanese house" or "exposed outside unshielded" was available from earlier studies and surveys (Ishida and Beebe, 1959).

In the late 1970s, the T65D estimates for Nagasaki survivors were recalculated using a different hypocenter and burst height for the bomb (Kato and Schull, 1982), and the dose estimates for survivors in both cities were redesignated as T65D Revised (T65DR). There were no changes in the dose estimates for Hiroshima survivors, and the changes for the Nagasaki survivors were small (less than 10%). Hence, it needs to be noted that sometimes the T65DR estimates for survivors may be referred to simply as T65D estimates (Kerr, 1989). The hypocenters and burst heights used in the various dosimetry studies are discussed in reports by Milton and Shohoji (1968), Kato and Schull (1982), and Kerr et al. (RERF, 1987, Vol. 1, pp. 66-142).

2. Tentative 1957 Doses (T57D)

During Operation Teapot at the Nevada Test Site (NTS) in 1955, ORNL, in cooperation with the Los Alamos National Laboratory (LANL), conducted a series of experiments that provided a much better understanding of weapon radiation fields. The results of these Operation Teapot experiments indicated the possibility of a definitive description of radiation fields from the Hiroshima and Nagasaki bombs (Kerr et al., 1992).

Consequently, in early 1956, a survey team visited ABCC in Hiroshima and Nagasaki to determine the feasibility of a dosimetry study. This survey team included Sam Hurst and Rufus Ritchie of ORNL, Payne Harris of LANL, Bill Ham of the Medical College of Virginia, and Bob Corsbie of the U.S. Atomic Energy Commission (AEC). Several ABCC studies had already reported an elevated incidence of cataracts and leukemia in the surviving populations, especially in Hiroshima. After reviewing records and examining shielding configurations for survivors, the survey team recommended that a dosimetry program be initiated. Emphasis was to be placed on the shielding provided by Japanese-type houses because of the high structural uniformity of the houses and the large number of survivors who were inside such structures when exposed. As a result of the survey team's findings, an AEC-funded program was established at ORNL and designated as *Ichiban* — a Japanese word meaning first or number one — because it was considered to be one of the top-priority programs at ORNL during the late fifties and early sixties.

A pilot study of the shielding provided by Japanese houses was conducted during Operation Plumbbob at NTS in 1957 (Ritchie and Hurst, 1957). The materials used in their construction were shipped from Japan to NTS, and they were built by American craftsmen using ABCC plans and specifications for a typical medium-size one-story Japanese house (see Fig. 2). The imported materials included the framing and sheathing, the ceramic tiles and embedding clay for the roof, the bamboo lathing, and the oyster shells and seaweed for the stucco material of the walls. A number of large collimators were also fabricated and used to measure the angular distributions of neutrons and gamma rays from a nuclear weapon (Hurst, 1995). The original intention was to obtain the shielding of A-bomb survivors by the thousands of houses involved in the ABCC studies by a combination experimental and calculational approach, using the angular distributions as input information. However, this approach commonly referred to as the "globe technique" was eventually applied only to several hundreds of A-bomb survivors who were outside and shielded by structures or terrain or inside and shielded by concrete buildings (Auxier, 1977).

A total of 30 neutron detectors and 30 gamma-ray detectors were exposed at various locations throughout the two medium-size Japanese-type houses to measure what is now called in-air tissue kerma. Half of the detectors were exposed at a height of approximately 1 m (42 in.) above the floor, while the remainder were placed at approximately 2 m (84 in.) above the floor. The house transmission factors obtained as ratios of the in-air tissue kerma inside the house to the in-air tissue kerma outside the house are shown in Fig. 3 (Ritchie and Hurst, 1957). For both neutrons and gamma rays, it is seen that the transmission factor correlates very well with a simple parameter — the house penetration distance — defined as the distance measured along the ray path from the point of entry into the house [see Fig. 1(c)]. If there were no windows in a house, the radiation levels would be fairly uniform throughout the house. The windows facing toward the nuclear weapon allow some of the radiation to enter unattenuated, and the farther one moves from the windows facing the nuclear weapon, the smaller is this contribution (Ritchie and Hurst, 1957).

After completion of the analysis of data from Plumbbob, a summary of all dosimetry information applicable to the survivors was prepared and transmitted to the shielding group at ABCC. Designated as T57D, this tentative dosimetry served as a guide for determining dose values from the shielding histories of the exposed individuals. With the assignment of Ed Arakawa to Hiroshima from 1958 to 1960, the shielding results from the nuclear weapons test at NTS were applied in medical follow-up studies of the survivors by ABCC (Arakawa, 1960). These studies, together with the calculations for the weapon radiation fields by E. N. York of the Air Force Special Weapons Center (York, 1957), led to the assignment of gamma-ray and neutron doses to individual medical records of survivors instead of the previously used broad dose-value categories based on distance from the hypocenter of the bombs. The T57D system of dose estimation was first used in 1959 to derive dose response curves for leukemia among lightly shielded survivors of the two cities (Heyssel et al., 1959; Tomonaga et al., 1959).

The procedure for estimating radiation doses to survivors exposed in houses that were either unshielded or lightly shielded by neighboring houses was as follows. From Fig. 1(a), the distance from the hypocenter or ground range was computed (i.e., 1097 m), and the radiation levels in the open at that ground range in Hiroshima was then read from Fig. 4. With the help of Fig. 1(c), the house penetration distance was measured (i.e., the dashed line from the roof to the survivor), and the house transmission factors were then determined from Fig. 3. The computations of in-air tissue kerma within the house were performed separately for each radiation component (i.e., neutrons and gamma rays) and for each exposed individual.

York's dose curves in Fig. 4 were in general agreement with the results of an earlier 1951 study by R. R. Wilson (1956). In this earlier study, Wilson concluded that the ratio of neutrons to gamma rays was quite different at Hiroshima and Nagasaki, and one might hope to separate the radiological effects due to gamma rays and neutrons by a comparative study of the effects in the two cities. At Hiroshima, neutron effects might predominate, whereas at Nagasaki, the situation was reversed and nearly all the radiation dose was due to gamma rays. To improve the radiation dose estimates for atomic bomb survivors, Ritchie and Hurst (1957) suggested that it would be necessary to (1) establish more accurate source terms for neutrons and gamma rays from the Hiroshima and Nagasaki bombs and (2) obtain information on radiation shielding by more general house configurations.

3. Tentative 1965 Doses (T65D)

Following Operation Plumbbob, laboratory studies of the shielding coefficients of Japanese and American building materials were conducted by John Auxier, Fred Sanders, and Wendell Ogg. Cement-asbestos board, commercially available in large sheets, was found to be suitable as a substitute for the mixture of clay, oyster shells, and seaweed wall plaster and for the embedding clay and tile roofs of Japanese houses for both neutrons and gamma rays. The wood framing used in Japan fitted well with the substitution of cement-asbestos board, and domestic materials were used to construct Japanese house replicas for shielding studies during later weapon tests at NTS (see Fig. 5).

During Operation Hardtack II in 1958, a large number of collimators were used for measuring the angular distributions of the neutrons and gamma rays from a nuclear weapon, and seven replicas of Japanese houses were constructed for the shielding studies. Three different floor plans which represented about 90% of all single family dwellings in Hiroshima and Nagasaki were used to construct the seven house replicas (i.e., three small one-story tenement houses, two medium-size one-story houses, and two large two-story houses). Emphasis was placed on evaluating the shielding as functions of house size, orientation, and position relative to other nearby houses. Because of the durability of the wall board, six of the seven houses were repaired and used three times and the seventh was used twice. The measurements at weapon test sites ended with the Limited Test Ban Treaty of 1962.

Consequently, it was decided to do a definitive study of the radiation fields at large distances from a small unmoderated and unshielded reactor. Designated as Operation BREN (Bare Reactor Experiment Nevada), the experiments were conducted under the leadership of John Auxier and Fred Sanders during the spring and early summer of 1962. The reactor was mounted on a hoist car, which was in turn mounted on a 465-m tower at NTS and operated at various heights above ground to simulate the prompt neutron and gamma-ray fields from a nuclear weapon. At 465 m (1527 ft.), the BREN tower was taller than the Washington Monument at 169 m (555 ft.), the Eiffel Tower at 300 m (984 ft.), and the Empire State Building at 448 m (1472 ft.). A ^{60}Co source of about 1200 curies was to simulate the delayed gamma-ray field from the fireball of a nuclear weapon following the completion of the reactor studies.

During Operation BREN in 1962, extensive measurements were made of the radiation fields in the open, in Japanese houses, and in clusters of Japanese houses. By the use of data from Operation BREN and earlier weapon tests, Cheka et al. (1965) developed a set of nine-parameters formulas that could be used to calculate the transmission factors for survivors exposed inside houses in either city. The nine parameters allowed these factors to be calculated as functions of such things as house size and orientation, location of a survivor inside the house, house penetration distance, location of the house with respect to nearby structures, and proximity of a survivor to an unshielded window facing toward the bomb.

The primary techniques for obtaining transmission factors in the T65D system of dose estimation for A-bomb survivors were as follows:

- The nine-parameter formulas for survivors exposed inside either one- or two-story Japanese houses or smaller tenement houses (Milton and Shohoji, 1968, pp. 42-43).

- The globe technique of determining transmission factors by a combination experimental and calculational approach, using measured angular distributions as input data (Noble, 1967, pp. 28-29 and 79-80).

- The *ad hoc* assignment of transmission factors based on a review of shielding histories or groups of similar shielding histories (Milton and Shohoji, 1968, pp. 8-9).

The globe technique was used for survivors who were either outside but shielded by a house or by terrain and for some survivors who were inside concrete buildings. Several important examples of *ad hoc* assignments within the T65D system were as follows:

- The use of averaged transmission factors for survivors who were known to be inside a Japanese house but for whom shielding histories were either incomplete or unavailable.

- The assignment of transmission factors of 0.9 or 1.0 for survivors inside factory buildings at Nagasaki and either shielded or unshielded by heavy equipment and machine tools, respectively.

- The assignment of transmission factors of 1.0 for all survivors who lacked shielding histories and were located at ground ranges of more than 1600 m in Hiroshima and 2000 m in Nagasaki.

Transmission factors and radiation doses were neither calculated or assigned for 3017 proximal exposed survivors because their shielding conditions were either extremely complex or unknown.

Following Operation BREN in 1962, Auxier et al. (1966) also developed a new set of dose curves for the weapon radiation fields in the open that were designated as T65D (see Fig. 6). Ideally, these dose curves would have been established from test firings of exact duplicates of the Japanese weapons. Some information was available from early tests of several Nagasaki-type weapons, but the Hiroshima bomb was the only one of its type that was ever fired, and the weapon radiation fields in Hiroshima had to be constructed using indirect evidence from calculations and experiments with nuclear reactors. However, the dose curves generated by the T65D equations were found to agree closely with results of independent studies by Hashizume et al. (1967) at the Japanese National Institute of Radiological Sciences (NIRS) and by Ichikawa, Higashimura, and Sidei (1966) at the University of Kyoto (see Fig. 6).

The gamma-ray doses of Ichikawa and co-workers were derived using thermoluminescence of quartz crystals from roof tiles. Some rather large uncertainties were involved in the estimated ground ranges. Since roof tiles were used only on Japanese houses and all houses close to the hypocenter were destroyed, the exact location of the each roof tile ATB was in doubt. The gamma-ray and neutron doses in the NIRS study were derived using the gamma ray-induced thermoluminescence of quartz crystals in decorative tiles and bricks and the neutron-induced ^{60}Co radioactivity in steel reinforcing bars (rebars) taken from commercial buildings that had been repaired and used for a number of years after the bombings. The exact location of each sample ATB was well-known, and the uncertainties in the estimated ground ranges were minimized. The NIRS study seemed to confirm the T65D results, and the T65D dose curves for the weapon radiation fields in both cities were used with a great deal of confidence in risk assessment throughout the 1970s.

Finally, the transport of radiation in the body of the survivors was calculated by Troyce Jones and co-workers in the 1970s (Jones et al., 1975), and the results were provided to the RERF as sets of organ dose factors which allowed one to account for the self-shielding of internal organs by overlying tissues of the body (Kerr, 1979). For leukemia, the organ of interest was the active bone marrow, and for other cancers, the specific organs of interest were the female breast tissue, lungs, stomach, etc. For studies of survivors exposed *in utero*, the radiation dose to the fetus was needed, and for studies of first generation (F_1) offspring of survivors, the radiation doses to the testes and ovaries of the F_1 parents were important. The absorbed doses to the deeply seated internal organs and fetus were significantly less than the T65D estimates of in-air tissue kerma for survivors which served only as an approximation to the maximum absorbed dose at the surface (skin) of the body (see, for example, Committee on the Biological Effects of Ionizing Radiations, 1972, p. 101).

4. Dosimetry System 1986 (DS86)

In the late 1970s, it was suggested that there were serious inadequacies with the T65D system, and these inadequacies were discussed at two symposia held in 1981 (Sinclair and Failla, 1981; Bond and Thiessen, 1981). The starting point for these discussions was the source term calculations for the Hiroshima and Nagasaki bombs by W. E. Pregg of LANL (Bond and Thiessen, 1981, pp. 125-130). In early 1983, joint U.S.-Japan research programs were established to conduct a thorough review of all aspects of the radiation dosimetry for the Hiroshima and Nagasaki A-bomb survivors (RERF, 1983; RERF, 1984). The review was completed in 1986 and the new DS86 system of dose estimation was adopted for use (RERF, 1987; Shimizu et al., 1988).

Two conditions were set on the cohort selected for dose estimation using the DS86 methods: (1) each individual must have a T65D (or T65DR) estimate, and (2) each individual must be a member or parent of an offspring in a major study sample (see Fig. 7). The total cohort due to overlap among the populations of the various samples is approximately 141,600 individuals (i.e., the 120,000 survivors of the LSS Sample plus the 1600 survivors of the *In utero* Clinical Sample and the 20,000 F_1 parents who are not part of the LSS Sample).

To facilitate the application of the DS86 methods of dose estimation for individual survivors, a modular computer code system was developed (RERF, 1987, Vol. 1, pp. 405-431). The DS86 methods were embodied in this code system as follows:

- A data base for the weapon radiation fields in the open which specifies the differential energy and angular fluences of neutron and gamma rays at four different heights above ground and at 25-m intervals from 100 to 2500 m of ground range in both cities (RERF, 1987, Vol. 1, pp. 66-142).

- A data base for house shielding cases which described how the differential neutron and gamma-ray fluences were modified at over fifty locations inside a Japanese house (or house cluster) and at a similar number of locations in which a survivor was outside and either partially shielded or totally shielded by a Japanese house (RERF, 1987, Vol. 1, pp. 227-305).

- A data base for organ dosimetry which describes how the differential neutron and gamma-ray fluences were further modified at 15 internal organ sites as functions of a survivor's orientation and posture ATB (RERF, 1987, Vol. 1, pp. 306-404). Age-dependent organ tissue doses can be made for infants (less than 3 years old ATB), children (3 to 12 years old ATB), and adults (more than 12 years old ATB).

Since the DS86 Final Report was published, two additional shielding data bases have been added to the modular computer code. One of these data bases was developed for application to terrain shielded survivors at Nagasaki (the data base for terrain shielding in the DS86 Final Report was never used and it was later replaced by a more refined data base for terrain shielding), and the other data base was developed for application to factory shielded survivors at several sites in Nagasaki (the Ordnance Plant at Oshashi, Steel Works at Mori-machi, and Dockyards at Saiwai-cho).

Suppose a survivor was exposed inside a small one-story Japanese-type house as illustrated in Fig. 8. First, the house was positioned about the survivor to simulate his or her actual shielding configuration ATB, and both the house and individual were positioned at the correct ground range from either the Hiroshima or Nagasaki bomb. Next, the differential particle fluences from the data base for the radiation fields in the open for the appropriate city were coupled with the adjoint particle fluences from the data base for house shielding to obtain the radiation fields inside the house. Finally, the adjoint particle fluences from the data base for organ doses were coupled with the radiation fields inside the house to provide organ tissue doses (as functions of age, posture, and orientation of the individual ATB) and in-air tissue kermas (inside and outside the house). This same procedure was used with the data bases for other shielding situations (i.e., outside shielded by a house, inside a factory building, etc.).

Because of the expense of a re-examination of the shielding histories, the DS86 data base for house shielding was constructed to use computerized shielding data that had been coded for T65D. Unlike T65D, however, DS86 does not make use of transmission factors or organ-dose factors *per se*, and organ tissue doses and in-air tissue kermas were calculated directly for survivors with shielding histories if the following conditions were satisfied:

- Inside a Japanese-type house or tenement for which 9-parameter data were coded (18,315 individuals).

- In the open but shielded by a Japanese-type house or tenement for which globe data were coded (3806 individuals).

- In the open but shielded by terrain features for which globe data were coded (361 individuals).

- In the open and unshielded with thermal flash burns reported on exposed portions of the face, neck, or arms (1297 individuals).

- Inside a steel frame factory building of light construction in Nagasaki without any additional shielding by heavy equipment or machine tools (815 individuals).

For survivors without shielding histories, it was necessary to develop supplemental techniques for indirect computation of the in-air tissue kerma and organ tissue doses. The various supplemental techniques for dose estimation are as follows:

- The use of an in-air tissue kerma of zero at ground distances of more than 2560 m in Hiroshima and 2760 m in Nagasaki where the in-air kermas to shielded survivors were less than 0.005 Gy (45,405 individuals).

- The use of averaged transmission factors and organ doses for survivors with limited shielding data which identified them as being exposed inside Japanese-type houses or tenements ATB (25,962 individuals).

- The use of averaged transmission factors and organ doses for survivors with limited shielding data which identified them as being exposed outside with or without shielding by houses or terrain ATB (10,034 individuals).

For this latter group, the in-air tissue kermas and organ tissue doses are less than 0.2 Gy in Hiroshima and less than 0.1 Gy in Nagasaki. Most of these survivors have been used traditionally as control subjects, and their addition to the LSS study sample offers little in the assessment of somatic risks. The primary reason for this extension of DS86 was to meet the special needs of the genetic studies. An offspring of two exposed parents may not be part of the control group for the assessment of genetic risks, and the offspring may be classified as a DS86 unknown-dose case if the radiation doses are not available for both parents. Thus, the use of this extension of DS86 is considered optional in the analyses of data from the different study populations (see Table 1).

Currently, DS86 estimates using either direct or indirect methods are available for 105,995 individuals or 92% of the total of 115,190 survivors who are members of the LSS and *In utero* Samples or parents of offspring in the F_1 Mortality Sample (see Table 3). However, there are now 9024 survivors without DS86 estimates (DS86 unknown) compared to only 3017 survivors without T65D estimates (T65D unknown). Most of the DS86 unknown-dose cases are proximal exposed survivors who were exposed in the open without flash burns, inside very heavily shielding structures (e.g., concrete buildings or air-raid shelters), or in very complex shielding situations (e.g., inside street cars, etc.).

Figure 9 presents a comparison of the DS86 and T65D curves for the radiation fields in the open at Hiroshima and Nagasaki, and Table 4 presents a comparison of DS86 and T65D values of the radiation doses for an adult A-bomb survivor exposed inside a Japanese-type house at 1200 m of ground range in both cites. The latter DS86 and T65D values can be compared directly because they were derived in a consistent manner (i.e., the DS86 values are based on house transmission factors and organ dose factors derived as averages from direct DS86 estimates for all survivors who were exposed inside Japanese-type houses or tenements). The principal differences between these two dosimetry systems can be summarized as follows:

- In Hiroshima, the gamma-ray kerma is larger than before, due in part to a change in bomb yield from the T65D value of 12.5 kiloton to the DS86 value of 15 kiloton, whereas in Nagasaki, the bomb yield and gamma ray kerma have remained essentially the same as before (see Fig. 9).

- In both Hiroshima and Nagasaki, the neutron kermas are significantly less than before for a couple of reasons (see Fig. 9). One reason is that the newer source terms suggest that the prompt neutrons coming from the Hiroshima bomb are more degraded in energy than thought previously (RERF, 1983, pp. 13-39), and the other reason is that the high humidity in Hiroshima and Nagasaki was not adequately taken into account before (i.e., modern weapon calculations indicate a reduction by a factor of two in neutron kerma because of the higher humidities, all other things being equal). The DS86 values suggest that neutrons are no longer a significant contributor to the radiation doses for Hiroshima survivors, and survivors in both cities were exposed mainly to gamma rays (see Table 4).

- The newer DS86 values for the transmission of gamma rays by houses are about half of the T65D values [i.e., the average transmission factors are 0.90 (T65D) versus 0.46 (DS86) in Hiroshima and 0.81 (T65D) versus 0.48 (DS86) in Nagasaki]. Thus, the T65D system seriously overestimated the transmission of gamma rays by houses (see Table 4). The newer DS86 values for the transmission of neutrons by houses have remained about the same as the T65D values [i.e., the average factors for the two systems are 0.36 (T65D) versus 0.46 (DS86) in Hiroshima and 0.35 (T65D) versus 0.41 (DS86) in Nagasaki].

- Organ dosimetry was not included as part of the original T65D system, but techniques for the estimation of organ tissue doses were added later. These techniques have now been found to seriously underestimate the tissue transmission of gamma rays by a factor of as much as two in the case of the deeply seated internal organs (Kerr, 1989). However, the increased tissue transmission for gamma rays in the DS86 system is largely or wholly offset by the changes in the house transmission factors, except in the case of a few superficial organs such as the female breast (see Table 4).

5. Discussion

One major task of the recent dose reassessment studies was to test the DS86 calculations to the maximum extent feasible. For example, considerable effort was made to extend the thermoluminescent (TL) measurements of the 1960s to longer ground ranges in both cities (RERF, 1987, Vol. 1, pp. 143-184). These TL measurements as well as the newer TL measurements of the DS86 study are shown in Fig. 10 as functions of the slant range which is the distance from the weapon's burst point in air to a point of interest at or near the ground. The slant range is used here to account differences in the heights of the various TL samples above the ground. It should be noted that the DS86 calculations for the gamma-ray fields in the open are in close agreement with the TL measurements at the longer ranges where there are considerable differences between the DS86 and T65D values (see Fig. 9). The TL measurements are discussed in reports by Ichikawa and colleagues (Ichikawa et al., 1967; Ichikawa et al., 1987; Hoshi et al., 1987) and the staff of the NIRS in Japan (Hashizume et al., 1967; Maruyama et al. 1987).

A major disappointment of the DS86 study was the poor agreement between calculations and measurements of cobalt activation by slow neutrons at both Hiroshima and Nagasaki (Loewe, 1985; Kerr et al., 1990; Kimura and Hamada, 1993). Recently, it has been found that the DS86 neutron calculations were in close agreement with a newer and more extensive set of measurements at Nagasaki for chlorine activation by slow neutrons (Straume et al., 1994). However, the new chlorine-activation data have also confirmed the previously noted discrepancy in the cobalt activation at Hiroshima (see Fig. 11). At Hiroshima, the calculated-to-measured ratios for cobalt activation are always greater than one at shorter ranges (i.e., less than 600 m of ground range or 840 m of slant range) and always less than one at longer ranges. Thus, the DS86 neutron calculations for Hiroshima appear to be too low by factors ranging from 2 to 10 at the ranges of most interest in the A-bomb survivor studies (i.e., 1000 to 2000 m of ground range or 1160 to 2080 m of slant range).

A set of new ORNL calculations have been made recently by Rhoades et al. (1994) to obtain neutron kermas that were consistent with the various neutron activation data at Hiroshima (see Fig. 12). Once a neutron source term was found that reproduced the neutron activation by fast neutrons in sulfur and by slow neutrons in cobalt, chlorine, and europium to within approximately 20% at all ranges, it was used to calculate the in-air tissue kerma from neutrons and from neutron-produced gamma rays in air and ground which were then added to the other gamma-ray components of the weapon radiation fields in the open. The good agreement is maintained with the DS86 gamma-ray values (and the TL measurements shown in Fig. 10), even though the new ORNL calculations are a factor of five greater than the DS86 neutron values and only a factor of two less than the T65D neutron values over the ranges of most interest in the A-bomb survivors studies (i.e., 1000 to 2000 m of ground range or 1160 to 2080 m of slant range). Based on these new ORNL calculations, it appears that the DS86 system grossly underestimates the in-air tissue kerma and organ tissue doses from neutrons in Hiroshima (see Fig. 12). Thus, top priority should be given in the immediate future to a more complete resolution of the causes for the DS86 neutron discrepancy and to the testing of its potential impact on the current estimates of the radiation risks and relative biological effectiveness (RBE) for neutrons that are derived from the A-bomb survivor studies.

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Table 1. Major study populations.

Study	Approximate number of subjects	Year base populations established	Year studies initiated
Survivors:			
Life span Study (LSS)	120,000	1950[a]	1958
Adult Health Study (AHS)	23,500	1950[a]	1958
In utero Mortality	2,800	1945-46[b]	1960
Offspring of survivors:			
First Generation (F_1) Mortality	75,000	1946-85[c]	1960
Biochemical Genetics Study (BGS)	45,000	1946-85[c]	1975
Chromosome Aberrations	33,000	1946-85[c]	1967

[a] Special supplement to the 1950 National Census in Japan.

[b] Birth records from August 1945 through June 1946.

[c] Birth records from June 1946 through December 1985.

Table 2. Inventory of shielding histories for proximal exposed survivors by shielding category.

City	Shielding category	Number	Percent
Hiroshima	Outside-unshielded	2,490	12.2
	Outside-partially shielded	547	2.7
	Outside-shielded by terrain	46	0.2
	Outside-shielded by a house	2,463	12.1
	Inside-Japanese house	14,130	69.4
	Inside-concrete building	329	1.6
	Inside-factory building	33	0.2
	Inside-air raid shelter	46	0.2
	Miscellaneous shielding	275	1.4
	Total all categories	20,359	100.0
Nagasaki	Outside-unshielded	513	6.1
	Outside-partially shielded	625	7.5
	Outside-shielded by terrain	392	4.7
	Outside-shielded by a house	1,125	13.5
	Inside-Japanese house	3,660	43.8
	Inside-concrete building	616	7.4
	Inside-factory building	1,047	12.5
	Inside-air raid shelter	336	4.0
	Miscellaneous shielding	41	0.5
	Total all categories	8,355	100.0

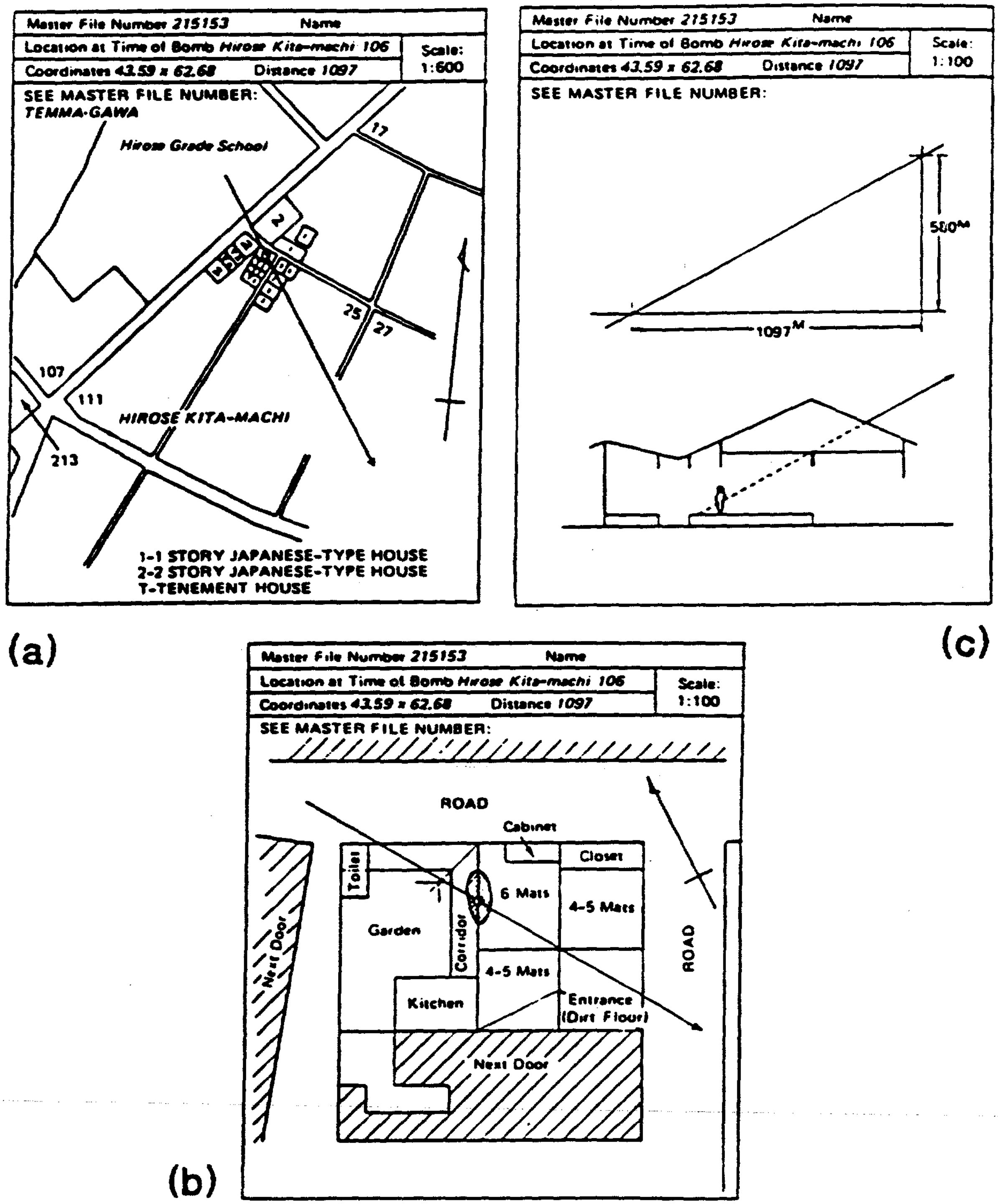
Table 3. Inventory of DS86 estimates for individual survivors.

Estimation method	Number of individuals
Direct DS86 estimates	24,594
Indirect DS86 estimates	81,401
Total DS86 estimates	105,995
Unknown DS86	9,024
Total DS86 cohort	115,019
Not-in-city (NIC)	26,616
Sample totals	141,635

Table 4. Comparison of radiation doses for an adult A-bomb survivor exposed inside a Japanese-type house at 1200 m of ground range.

City	Dosimetric quantity	Dose system	Average radiation dose (Gy)		
			Total	Gamma rays	Neutrons
Hiroshima	In-air tissue kerma	DS86	0.783	0.762	0.021
		T65D	1.041	0.855	0.186
	Female breast tissue	DS86	0.663	0.650	0.013
		T65D	0.794	0.692	0.102
	Active bone marrow	DS86	0.634	0.626	0.008
		T65D	0.543	0.491	0.052
	Lung	DS86	0.619	0.612	0.007
		T65D	0.482	0.441	0.041
	Stomach	DS86	0.584	0.578	0.006
		T65D	0.450	0.415	0.035
	Large intestine	DS86	0.573	0.569	0.004
		T65D	0.382	0.356	0.026
Nagasaki	In-air tissue kerma	DS86	1.556	1.544	0.016
		T65D	3.219	3.186	0.037
	Female breast tissue	DS86	1.311	1.301	0.010
		T65D	2.570	2.550	0.020
	Active bone marrow	DS86	1.274	1.267	0.007
		T65D	1.797	1.787	0.010
	Lung	DS86	1.236	1.230	0.006
		T65D	1.604	1.596	0.008
	Stomach	DS86	1.175	1.170	0.005
		T65D	1.507	1.500	0.007
	Large intestine	DS86	1.160	1.156	0.004
		T65D	1.282	1.277	0.005

List of Figures



Master File Number 215153
Name
Location at Time of Bomb Hirose Kita-machi 106
Scale: 1:600
Coordinates 43.59 x 62.68
Distance 1097
SEE MASTER FILE NUMBER:
TEMMA-GAWA
Hirose Grade School
17
2
25
27
107
111
213
HIROSE KITA-MACHI
1-1 STORY JAPANESE-TYPE HOUSE
2-2 STORY JAPANESE-TYPE HOUSE
T-TENEMENT HOUSE
(a)
Master File Number 215153
Name
Location at Time of Bomb Hirose Kita-machi 106
Scale: 1:100
Coordinates 43.59 x 62.68
Distance 1097
SEE MASTER FILE NUMBER:
580M
1097M
(c)
Master File Number 215153
Name
Location at Time of Bomb Hirose Kita-machi 106
Scale: 1:100
Coordinates 43.59 x 62.68
Distance 1097
SEE MASTER FILE NUMBER:
ROAD
Cabinet
Closet
Toilet
6 Mats
4-5 Mats
Garden
Corridor
Next Door
4-5 Mats
ROAD
Kitchen
Entrance (Dirt Floor)
Next Door
(b)

Fig. 1

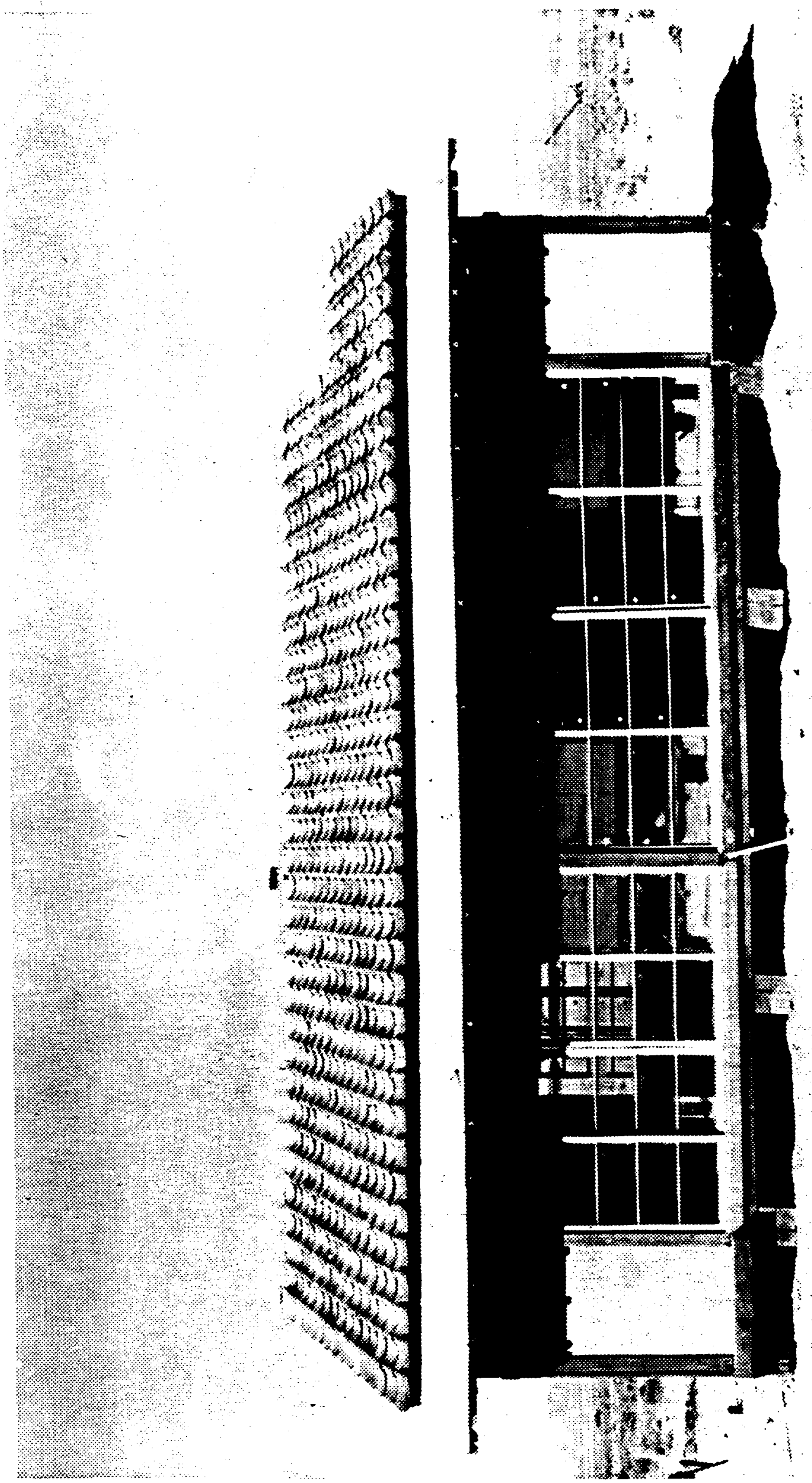
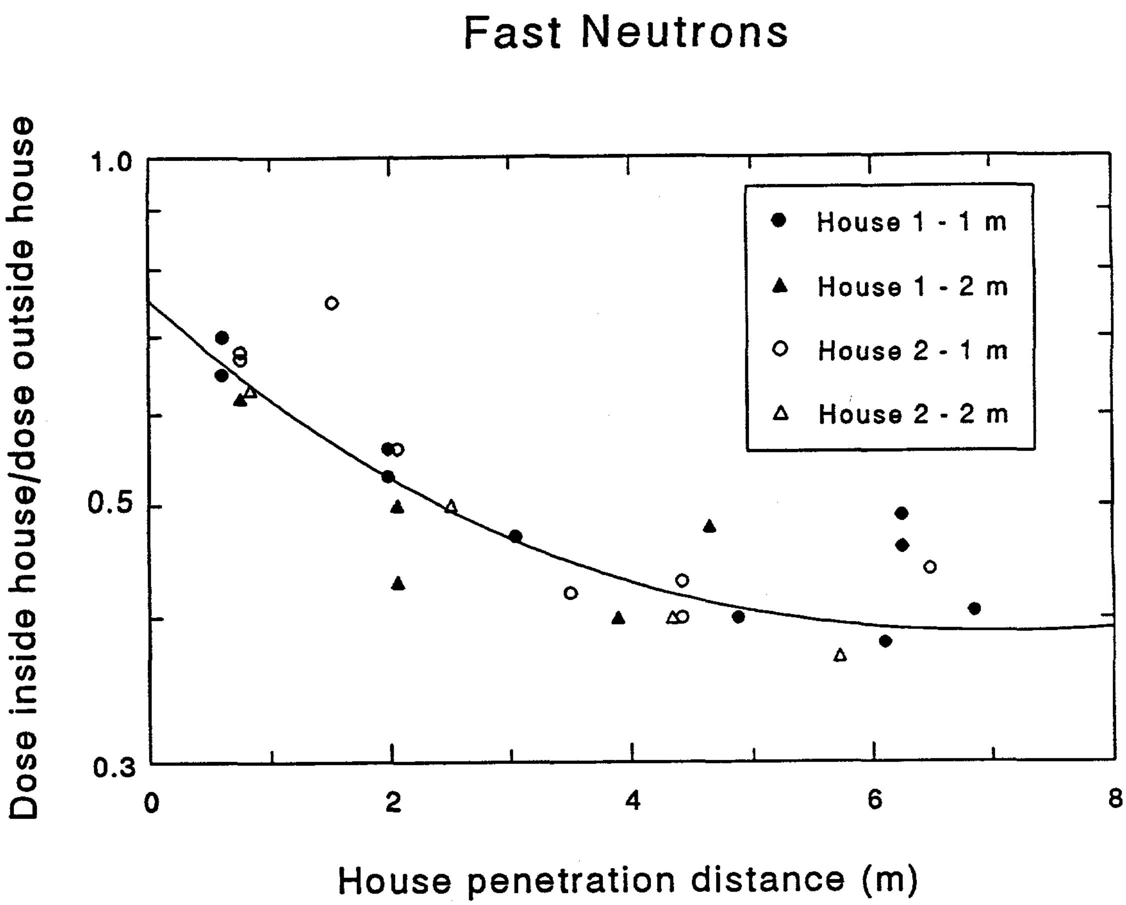


Fig. 2


Fast Neutrons
Dose inside house/dose outside house
1.0
0.5
0.3
0
2
4
6
8
House penetration distance (m)
House 1 - 1 m
House 1 - 2 m
House 2 - 1 m
House 2 - 2 m

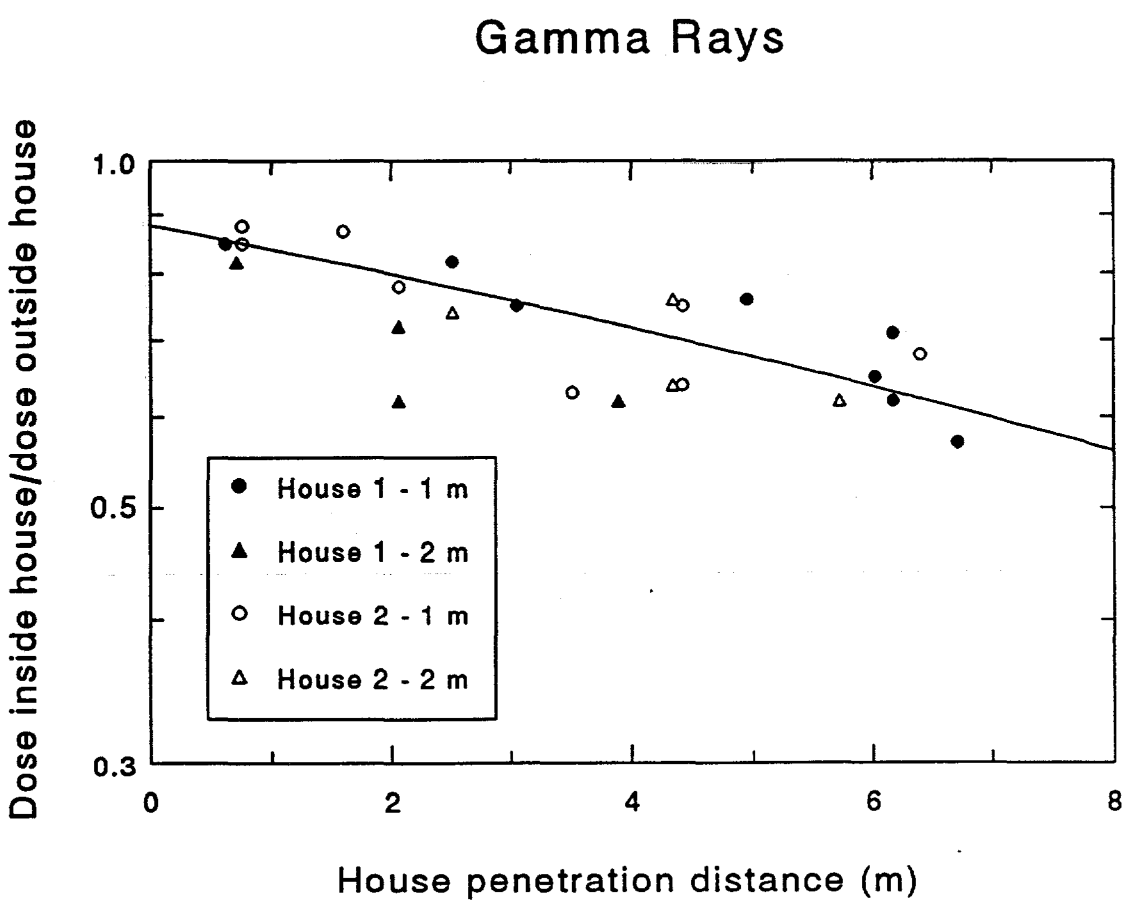
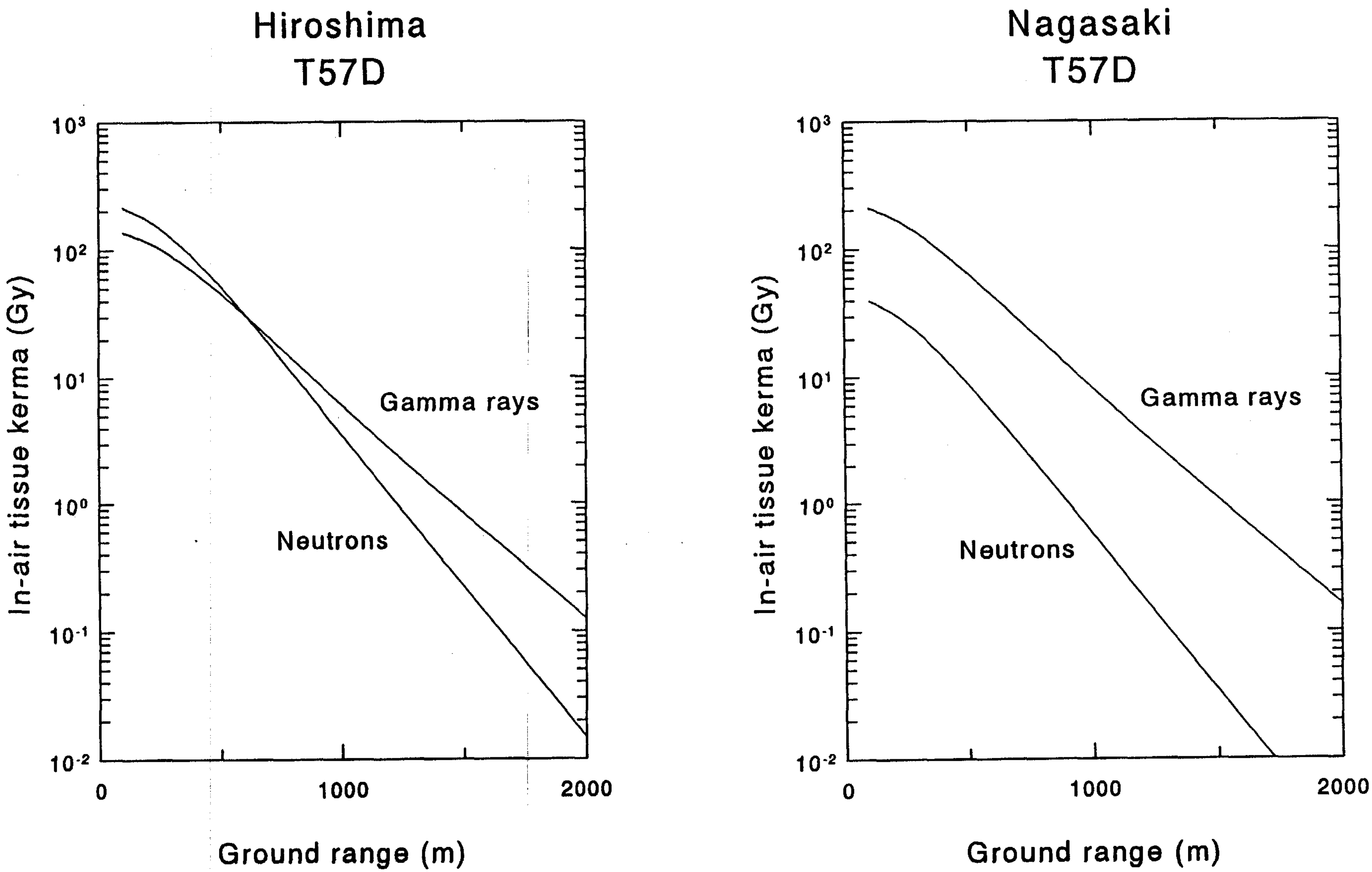

Gamma Rays
Dose inside house/dose outside house
1.0
0.5
0.3
0
2
4
6
8
House penetration distance (m)
House 1 - 1 m
House 1 - 2 m
House 2 - 1 m
House 2 - 2 m

Fig. 3



Hiroshima
T57D
In-air tissue kerma (Gy)
10^3
10^2
10^1
10^0
10^-1
10^-2
0
1000
2000
Ground range (m)
Gamma rays
Neutrons
Nagasaki
T57D
In-air tissue kerma (Gy)
10^3
10^2
10^1
10^0
10^-1
10^-2
0
1000
2000
Ground range (m)
Gamma rays
Neutrons

Fig. 4

CROP

CROP

Fig. 5

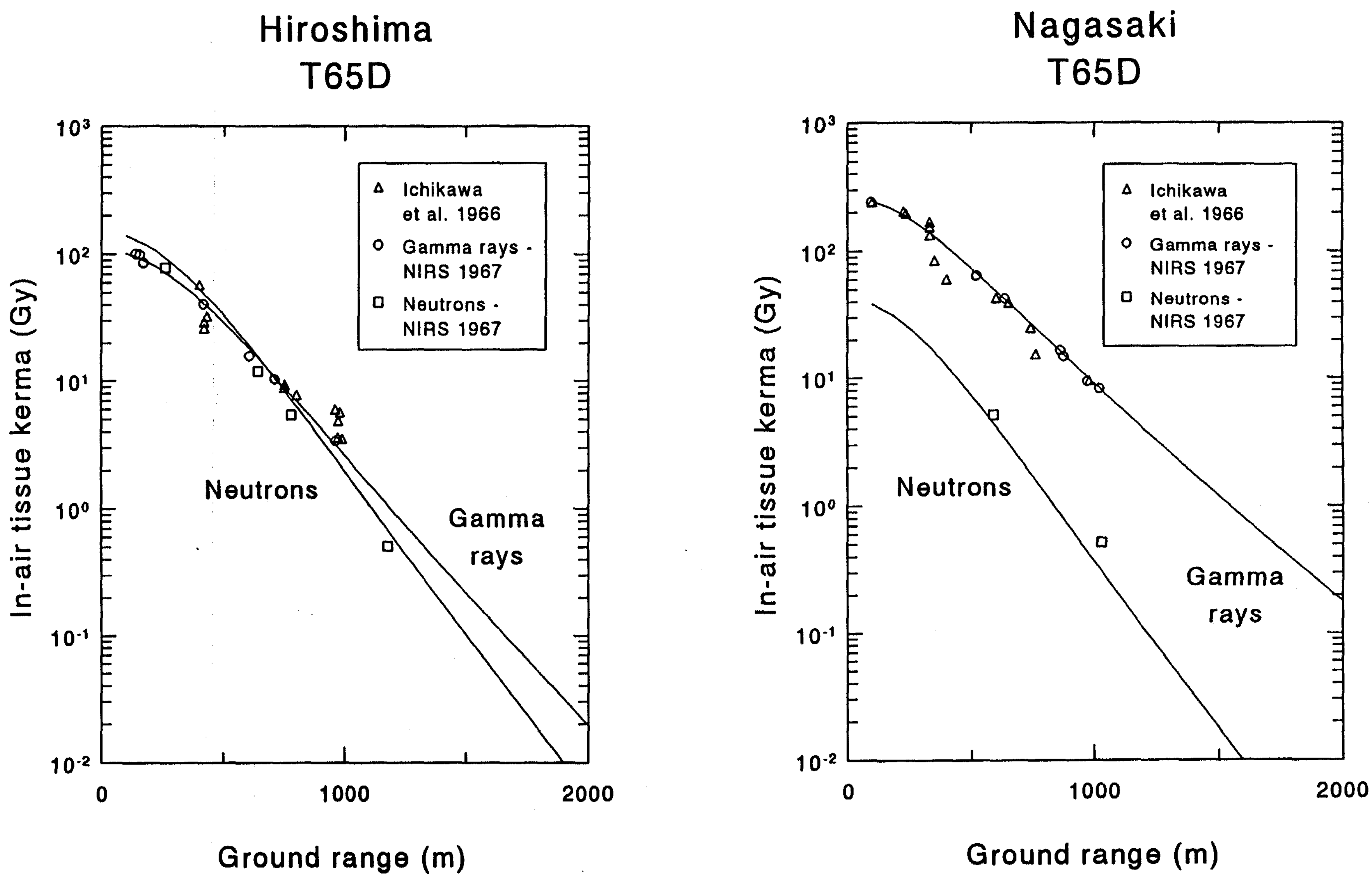

Hiroshima
T65D
Nagasaki
T65D
In-air tissue kerma (Gy)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
1000
2000
Ground range (m)
Ichikawa et al. 1966
Gamma rays - NIRS 1967
Neutrons - NIRS 1967
Neutrons
Gamma rays

Fig. 6

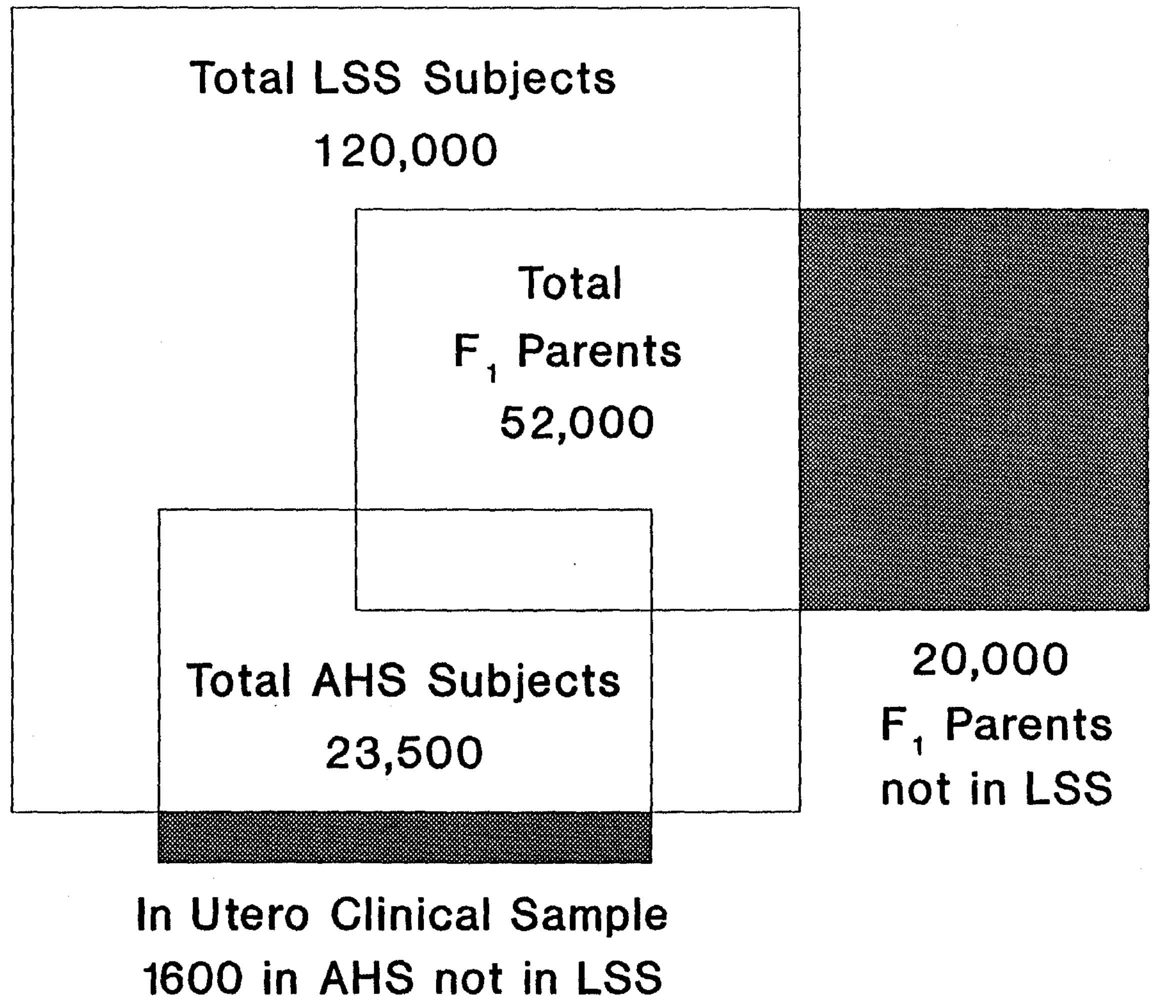

Total LSS Subjects
120,000
Total
F1 Parents
52,000
20,000
F1 Parents
not in LSS
Total AHS Subjects
23,500
In Utero Clinical Sample
1600 in AHS not in LSS

Fig. 7

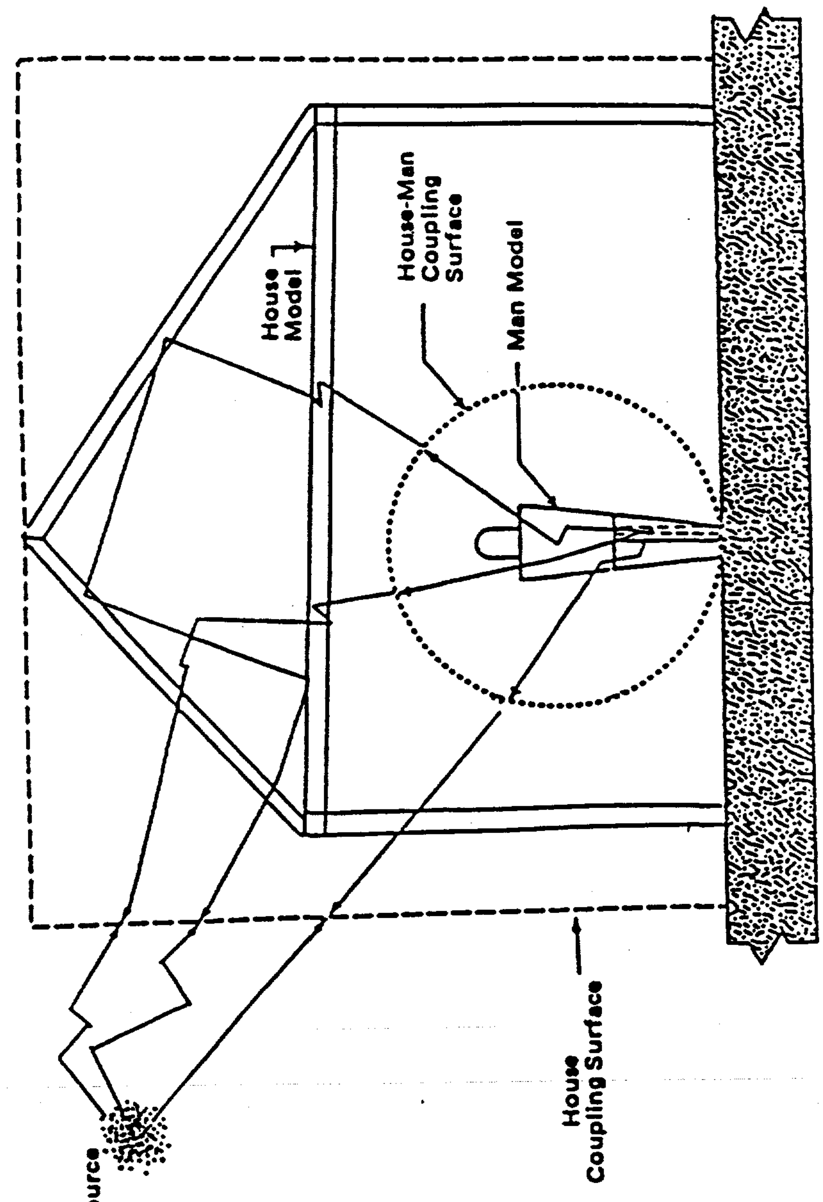

Source
House Coupling Surface
House Model
House-Man Coupling Surface
Man Model
Ground

Fig. 8

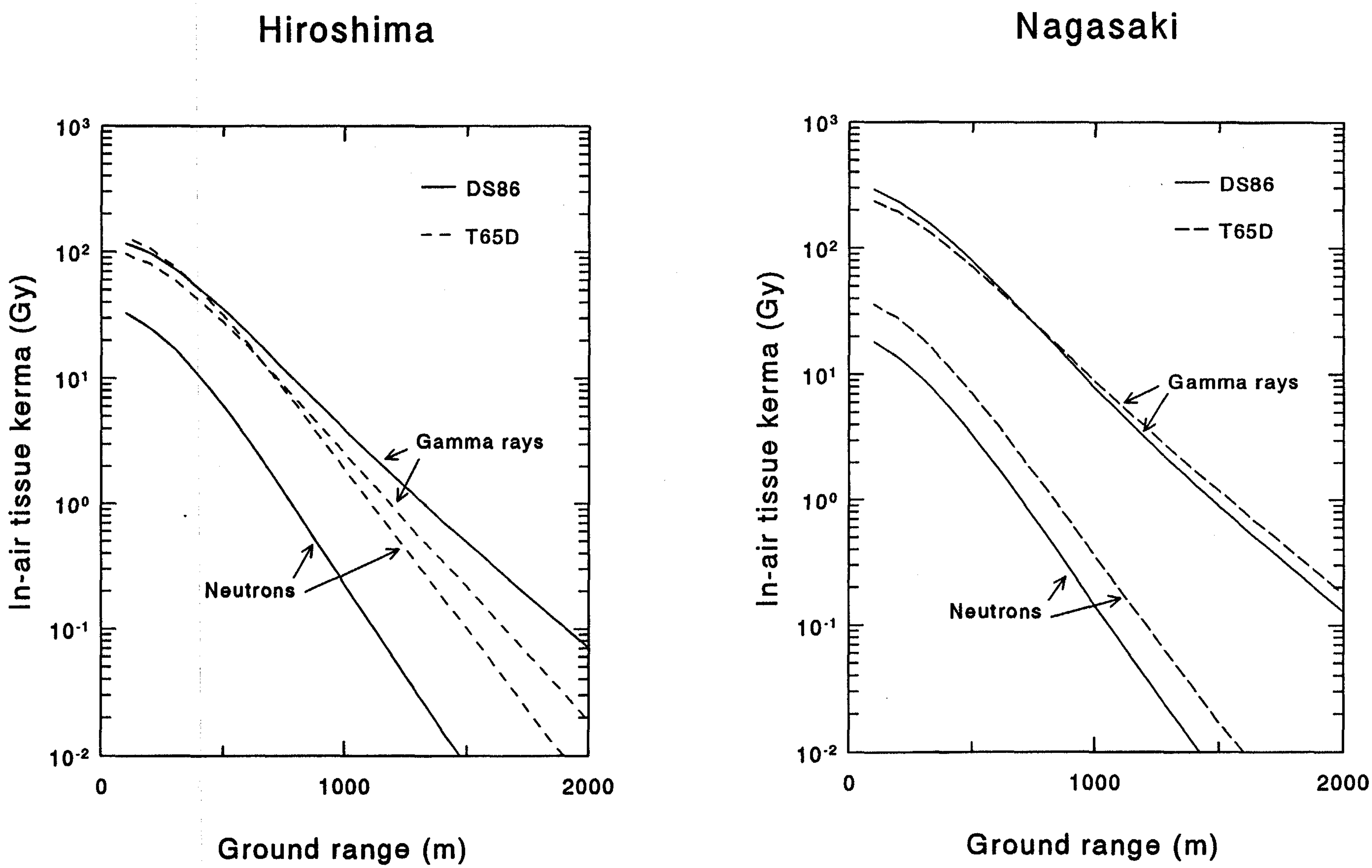
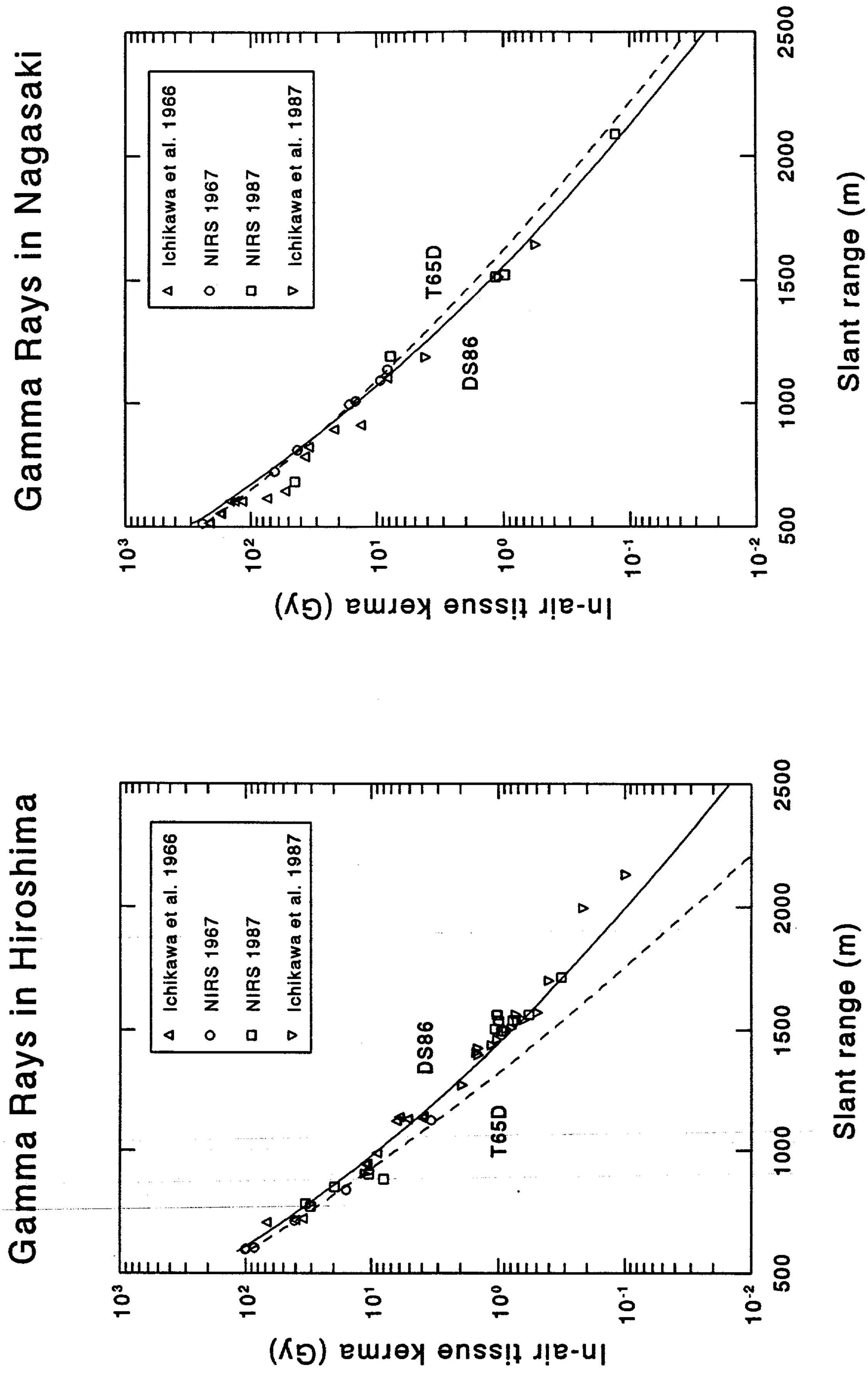

Hiroshima
Nagasaki
DS86
T65D
Gamma rays
Neutrons
In-air tissue kerma (Gy)
Ground range (m)
0
1000
2000
10³
10²
10¹
10⁰
10⁻¹
10⁻²

Fig. 9



Gamma Rays in Hiroshima
Ichikawa et al. 1966
NIRS 1967
NIRS 1987
Ichikawa et al. 1987
DS86
T65D
In-air tissue kerma (Gy)
Slant range (m)
Gamma Rays in Nagasaki
Ichikawa et al. 1966
NIRS 1967
NIRS 1987
Ichikawa et al. 1987
T65D
DS86
In-air tissue kerma (Gy)
Slant range (m)

Fig. 10

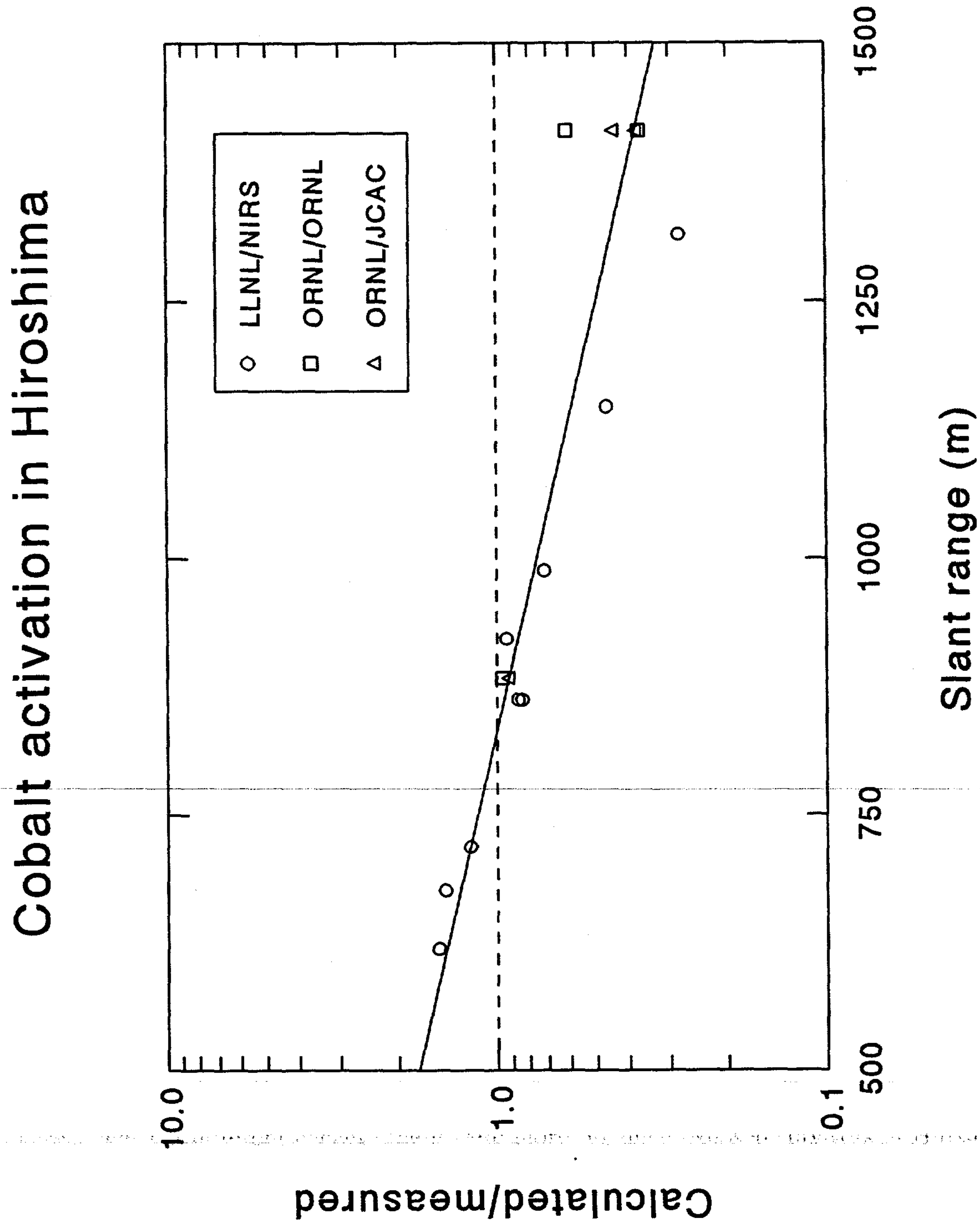

Cobalt activation in Hiroshima
Calculated/measured
10.0
1.0
0.1
500
750
1000
1250
1500
Slant range (m)
LLNL/NIRS
ORNL/ORNL
ORNL/JCAC

Fig. 11

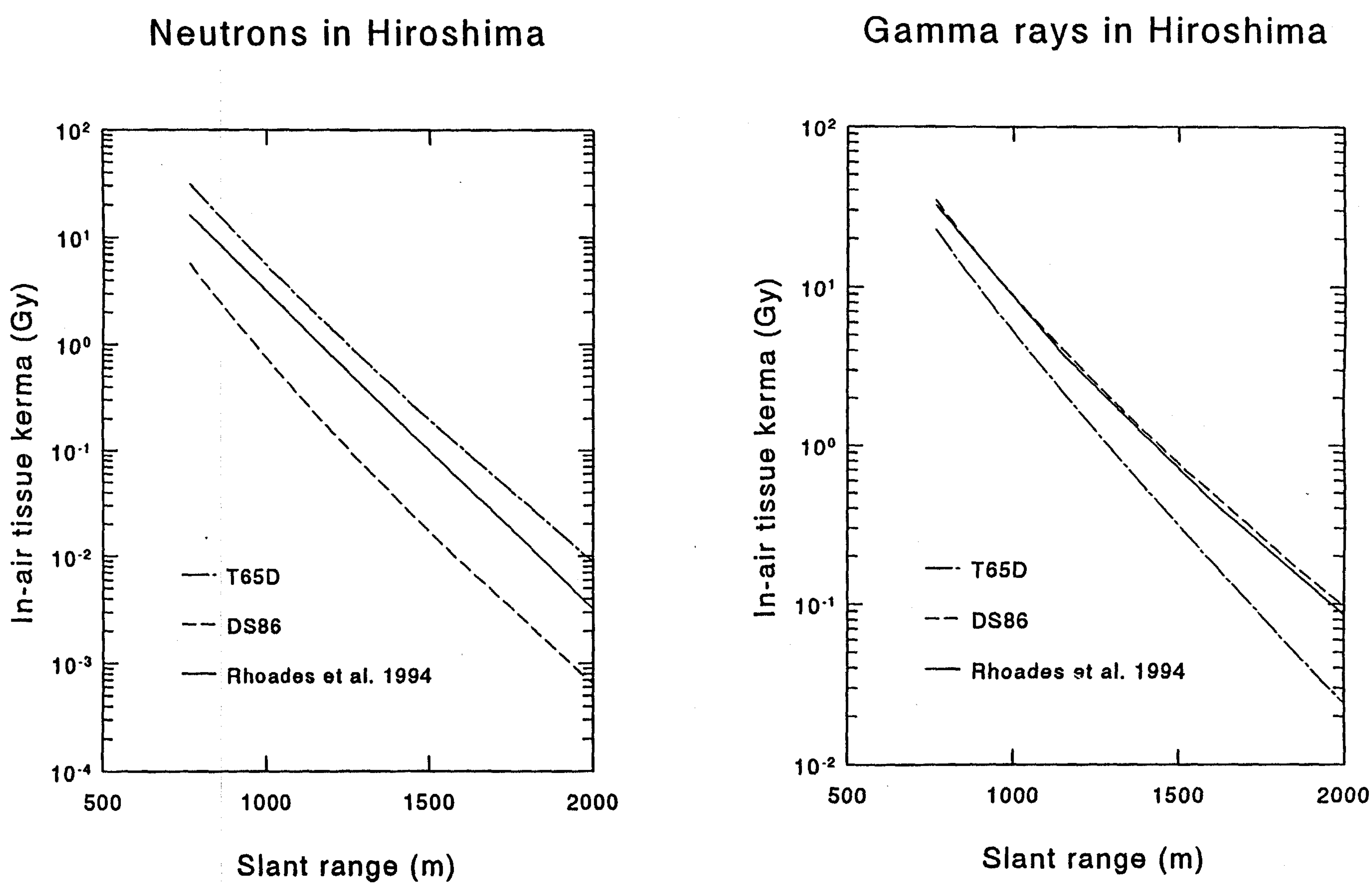

Neutrons in Hiroshima
In-air tissue kerma (Gy)
Slant range (m)
T65D
DS86
Rhoades et al. 1994
Gamma rays in Hiroshima
In-air tissue kerma (Gy)
Slant range (m)
T65D
DS86
Rhoades et al. 1994

Fig. 12