EXECUTIVE SUMMARY

Robert F. Christy
California Institute of Technology

Eizo Tajima
St. Paul's University; Nuclear Safety Commission

The *Historical Review* describes the events leading up to the present reassessment of the dosimetry of the atomic bombs at Hiroshima and Nagasaki. To make that reassessment, working groups were set up in Japan and in the United States. These groups organized their efforts into ten major areas: yields of the bombs, radiation leakage from the bombs, transport of radiation in air over ground, thermoluminescence measurements of gamma rays, measurements of neutrons, residual radioactivity, house and terrain shielding, organ dosimetry, preparation of a dosimetry system, and uncertainty analysis. In this report on the reassessment, one chapter is devoted to each of the first nine areas; a future report will deal with the last area, uncertainty analysis. The chapters were prepared by writing groups, listed as the authors of the chapters. The chapters are based on a large number of individual papers, some of which are included in this report as appendixes to the relevant chapters.

CHAPTER 1. YIELDS OF THE BOMBS

Most avenues to a determination of the neutron and gamma-ray doses at Hiroshima and Nagasaki start with the determination of the bomb yields as a basic measure leading to the total number of fissions in the sources and thereby, a measure of the source strength for prompt neutrons and gamma rays.

A number of different measures and some calculations provide information on the yields of the Hiroshima and Nagasaki bombs. The Nagasaki bomb was identical to the one studied at the Trinity bomb test and later at the Crossroads Able and Baker tests. Yields were determined by radiochemical evaluation of the debris in the fireball and by measuring the fireball expansion at Trinity and Crossroads. All these measures gave yields between 20 and 22 kt and agree with a calculated yield of 22 kt.

The measurements that bear on the yield of the Hiroshima bomb or the ratio of the yields of the two bombs include the following. It is assumed that a constant fraction (0.35) of the bomb energy is emitted as thermal energy from bombs of the types considered in this report. A number of thermal effects such as surface melting of tiles, flaking of granite, and charring of telephone poles have been compared in the two cities and can be used to determine the ratio of the yields. In addition, an absolute laboratory test was made to simulate the charring of cypress wood at a site 676 m from the hypocenter. These various measures are not very self-consistent and are suspect at large distances because of the attenuation due to the air but are consistent with a yield in the range 12 to 18 kt.

Blast effects were also compared in the two cities and also evaluated on an absolute basis by a group led by W. Penney. Penney's results were 12 ± 1 kt for Hiroshima and 22 ± 2 kt for Nagasaki. Recent improvements in the blast wave model will provide a basis for reevaluating this data. It appears likely that the Hiroshima yield may be increased by about 20% in this reevaluation, which is not yet complete. Other data, on relative blast damage, also are consistent with a yield difference of about 0.7, or a Hiroshima yield of about 15 kt based on 21 kt for Nagasaki.

Canisters were dropped by parachute at the same time as the bombs in Hiroshima and Nagasaki. These were instrumented with pressure gauges and radio transmitters. The data were recorded in the mission aircraft and provide (somewhat imperfect) records of pressure versus time showing the initial blast wave and the reflected blast wave. There are certain puzzles in the interpretation of these data associated with the slightly longer than expected delay in arrival of the signal. The Hiroshima record was interpreted to give a yield of 16.5 kt.

The fast neutron activation of sulfur was also used to evaluate the yield. Comparison of the measurements with calculations suggests a yield of 13 kt at Hiroshima. The gamma-ray dose to quartz in building materials, as determined from measurements of thermoluminescence, can also be evaluated to determine a yield. Differences between the various measurements prevent a precise conclusion at the present time. The reviewers suggest a yield of 18 kt for Hiroshima from these measurements.

The recommended yields for the two explosions, based on this review are 15 kt for Hiroshima and 21 kt for Nagasaki, where the value for the Hiroshima yield is assigned an outside limit of uncertainty of 20% or 3 kt and for the Nagasaki yield, 10% or 2 kt.

CHAPTER 2. CALCULATION AND VERIFICATION OF SOURCE TERMS

Given the yield, it is then necessary to determine the number and the distribution in energy and angle of the neutrons and gamma rays emerging from the bomb case. The emerging neutrons serve as one major source of gamma rays through their capture in air. The other major source of gamma rays is the cloud of fission products in the fireball in the first seconds after detonation, before radioactive decay reduces the source and before the fireball rises so high that little further radiation reaches the ground.

The actual emission of neutrons and gamma rays from the bombs can be determined only by complex calculations of the transport and the accompanying hydrodynamics in the exploding bombs. These calculations have been carried out both at Los Alamos National Laboratory (LANL) and at Lawrence Livermore National Laboratory (LLNL). The techniques used at the two laboratories are different and the results have sometimes disagreed, but the latest work of the laboratories is in reasonable agreement. To buttress these calculations there are a number of different types of measurements.

At LANL, a critical assembly was set up using parts of a bomb of the type exploded at Hiroshima, but with a reduced amount of ^{235}U. At this site, a number of measures of neutron emission were made and compared to a calculation made using the same technique as that used in the bomb explosions. These various calculated and measured neutron fluences now show good agreement (standard deviation of about 10%) at energies above 0.6 MeV and at all polar angles except 0° (nose direction) where the fluence is in any case very low. These results lend confidence to the calculated fast neutron emission of the Hiroshima bomb. Since it is the emitted neutrons above 1 MeV that are transported to distances of 1000 m or greater, there is a good basis underlying the calculated neutron doses.

A significant source of prompt gamma rays is the capture of neutrons by the nitrogen in air. These gamma rays are, therefore, controlled by the total neutron emission. Several independent measurements of the total neutrons down to very low energies agreed with calculations. This provides a verification of the calculations of prompt gamma rays from the Hiroshima weapon. Other weapon tests have provided good validation of calculations of the total sources of air-capture gamma rays. In particular, the Ranger-Fox test involved a bomb of design and yield similar to the Nagasaki bomb and detonated at a similar height. At this test, the total gamma rays were measured at distances beyond 900 m with good agreement with calculations.

The same critical assembly discussed above can provide a precise measure of the separation at which criticality is reached, a separation which is intimately related to the yield of bomb explosion. The calculated separation is within the experimental error of the measured value, which gives considerable confidence in the accuracy of the other computations.

As a result of the test described above we have considerable confidence in the calculated neutron energy and angular distributions from the Hiroshima weapon. Because of its near spherical symmetry and simpler design, there has not been much doubt about the calculated emission from the Nagasaki weapon.

CHAPTER 3. TRANSPORT OF INITIAL RADIATIONS IN AIR OVER GROUND

From the source of neutrons and gamma rays from the bomb, the radiations propagate through the air to the region where the dose is to be evaluated. Important input data for the calculations of dose are the location and height of the burst, the atmospheric density and humidity profiles, and the ground composition. Various studies of the burst locations were reviewed and a recommended set of coordinates was chosen. Ground samples were measured to determine ground composition and moisture. Also, several meteorological studies of the weather on the days of the bombings and days with closely similar weather conditions were used to provide an atmospheric profile of density and humidity.

The propagation in air is a major computational effort, which can now be carried out with considerable confidence for the radiations emitted from the bomb and for the gamma rays produced by neutron capture in the air. However, the details of the emission and propagation of the fission product gamma rays (and the so-called delayed neutrons) is much more complicated because the source (the fireball) is rising rapidly and undergoing complex and not well understood hydrodynamic motions.

The determination of the free-in-air kerma in tissue (see Editor's Note) at various relevant distances up to about 2000 m ground range is an essential step in estimating the dose to the survivors at Hiroshima and Nagasaki. The calculations of transport in air of the neutrons and gamma rays involve the source terms discussed in Chapter 2 and the bomb yields discussed in Chapter 1. In each case, the prompt neutron transport and the prompt and air capture gamma-ray transport are calculated using a discrete-ordinate two-dimensional computer code. Extensive calculation has also been carried out with a Monte Carlo code. In these "prompt" transport calculations, the air is assumed to be undisturbed (i.e., the transported neutrons and gamma rays escape ahead of the blast wave). It is possible that there is some interaction between the capture of neutrons in air and the fireball since the capture in air involves a delay of about 0.1 or 0.2 seconds, in which time the fireball grows to more than one mean free path in radius. This effect might necessitate a small correction to the air capture gamma rays but the calculation is very difficult and has not yet been made.

In addition to the prompt radiations, there is a considerable contribution to the gamma-ray dose from delayed radiations from the fission products in the rising fireball. The source of these radiations is the fission products and their energy and time dependence are needed from a few tenths of a second out to a few tens of seconds following fast neutron fission in ^{235}U, ^{238}U, and ^{239}Pu; not all of the data are available. These sources must be used in a time-dependent geometry since the fission products circulate within the fireball, an expanding region of very low density that rises because of its buoyancy. The gamma-ray transport under these conditions should be calculated by the same codes used to calculate transport within an exploding bomb. However, this would be very time consuming and has never been done (to our knowledge). As a substitute, approximate one-dimensional calculations, in which distances must be replaced by the integral of the density of the air over the distance, must be used. In addition, some effort is made to approximate the motion of the fission products within the fireball.

At a few bomb tests the gamma rays were measured as a function of time from a few tenths of a second to several tens of seconds. These measurements were used to verify models of the delayed gamma-ray calculation although the measurements do not deal with weapons of similar yield or similar height of burst to Hiroshima and Nagasaki. The final models of the delayed gamma radiation agree to about 10% with the time-dependent measurements at the weapon tests and lead to predictions at Hiroshima and Nagasaki that are expected to be accurate to better than 15%.

The delayed neutrons appear to make a significant contribution to the thermal neutron activation in Nagasaki and an apparently smaller contribution in Hiroshima. The delayed neutron calculations were carried out using the integral of density over radius to represent the complex air geometry after the burst. However, a few calculations show that the results of this method must be corrected downward by a factor of two-thirds. The resulting calculations were combined with the prompt neutron calculations in an attempt to fit thermal neutron activation data obtained at the Buster-Jangle and Ranger-Fox tests, which involved weapons similar to the Nagasaki bomb and detonated at a similar altitude. The agreement with measurement is good at distances greater than 1200 m, but calculation appears to be consistently high by factors approaching two at shorter distances. These same calculations were used in evaluating the cobalt activation data (Chapter 5). It appears that there are still some deficiencies in these calculations of thermal neutrons at ranges less than 1000 m. However, these deficiencies should not be important in the doses to the survivors.

In Chapter 3, the free-in-air kermas in tissue for neutrons and gamma rays for the new DS86 calculations are compared with the T65D system. At Nagasaki, the gamma-ray kerma for DS86 is smaller than that for T65D by about 10 to 30%, depending on ground range; the DS86 neutron kerma is about one-half to one-third that of T65D. The gamma-ray kermas agree within the errors with which they can be determined. The reduction in the neutron kerma is due to two changes in the new calculations: (1) the energies of the neutrons escaping from the bomb are lower, and (2) the effect of water vapor in the air was included, and this reduced the transmission of the neutrons because of the increase of the cross section of hydrogen with decreasing neutron energy.

At Hiroshima, the gamma-ray kerma for DS86 is larger than that for T65D by a factor ranging from about two to three and one-half, depending on ground range; the DS86 neutron kerma is about one-tenth that of T65D. A small part of these changes is due to a change in the yield used in the two dosimetry systems, from 12.5 to 15 kt. The rest of the change in the gamma-ray kermas (factors from 1.7 to 2.9) is due to changes in the method of determining the kermas. In DS86, the subject of this report, the calculations are from primary physical data. In T65D, methods were based on experimental data: bomb tests, the BREN experiments, and reactor leakage experiments. Bombs of the type exploded at Nagasaki were also used in tests in Nevada; consequently, there was a secure base of experimental data from which to calculate kermas. No bomb of the type exploded at Hiroshima was ever tested. The data for calculation of kerma had to be modified from that for Nagasaki-type bombs (see Chapter 9 for a brief description of how this was done). Unfortunately, something in these modifications did not turn out right. No attempt was made in the present reassessment program to retrace the T65D work to see where the difference arose. Clearly, however, the rate of attenuation of the gamma rays is distinctly different in the two systems. The neutron kerma at Hiroshima was reduced by the same effects that reduced the neutron kerma at Nagasaki. The reduction at Hiroshima was greater because the reduction in the energies of the neutrons in penetrating the bomb casing was greater.

The estimated errors in kerma in tissue from delayed gamma rays are of order 10 to 20%; the estimated errors in total neutron and total gamma-ray kermas between 1000 and 2000 m in Hiroshima and Nagasaki should be in the 10 to 20% range assuming the initial sources to be correct.

CHAPTER 4. THERMOLUMINESCENCE MEASUREMENTS OF GAMMA RAYS

There are certain approaches that provide direct measures of the gamma-ray and neutron doses at relevant distances. Thermoluminescence (TL) dosimetry has been developed in the last 30 years, and one of its goals was to evaluate the age of pottery specimens exposed to natural radiations. It has proved possible to use similar TL techniques to evaluate the gamma-ray dose delivered to small quartz inclusions in kiln-fired brick and tile taken from structures present in Hiroshima and Nagasaki at the time of the bombs. Higashimura, Ichikawa, and

Sidei first made such measurements in 1963, followed by Hashizume and Maruyama et al. In this way, direct measures of the gamma-ray doses have been made at distances from the hypocenter of more than 2000 m, where the doses are about 20 rad. Certain other techniques, such as electron spin resonance measurements on shell buttons and teeth, may also provide useful data in this context.

Recently, measurements were made by six laboratories, three in Japan, one in the United States, and two in England. They are the National Institute of Radiological Sciences (NIRS) in Chiba, Japan; Nara University of Education (NUE) in Nara, Japan; Hiroshima University in Hiroshima, Japan; the University of Utah in Salt Lake City, USA; Oxford University in Oxford, England; and Durham University in Durham, England.

These laboratories engaged in extensive intercomparisons and also in absolute calibrations. Measurements were made on a large number of well documented samples collected at various distances out to nearly 2100 m in Nagasaki and in Hiroshima. Free-in-air kermas measured at Hiroshima range from 10,000 rad near the hypocenter to about 35 rad at 1600 m. At Nagasaki, measured doses range from 20,000 rad to about 120 rad at 1427 m.

In order to compare the measured doses with calculations, a series of adjustments is required. First, all doses were converted to dose in quartz. This required adjustment of doses measured at NIRS and NUE, where doses are quoted for tissue. A multiplication factor of 0.917 was used. After several calibration attempts, the doses in quartz were corrected based on measurements of standard Mg_2SiO_4:Tb samples irradiated by the National Bureau of Standards and measured by the various laboratories.

Finally, the gamma-ray spectra at various distances in Hiroshima and Nagasaki were used and the sample in its actual location in a building was modeled in calculation of dose in the sample. This permits a final comparison of measured and calculated doses. The agreement or disagreement at this stage can be fed back into the yield determination and into the error and uncertainty analysis. The final results of this process give agreement in Nagasaki to within about 10% out to 1500 m, whereas they are within 25 or 30% out to 2100 m in Hiroshima.

Some other techniques have been used for dose determinations in Hiroshima and Nagasaki. Electron spin resonance was used on a shell button obtained from a doctor at a hospital 691 m from the hypocenter in Nagasaki. It also has been used on tooth enamel of persons exposed at various distances in both Hiroshima and Nagasaki. Because of the sometimes complex shielding of survivors, it can be difficult to compare these doses with calculations. But the technique could be invaluable in estimating doses to actual survivors to compare with symptoms.

CHAPTER 5. MEASUREMENTS OF NEUTRON FLUENCES

Shortly after the bomb exploded in Hiroshima, Japanese investigators measured the activity of ^{32}P induced by fast neutrons in sulfur used as glue on electric insulators at ground ranges out to 1000 m. The activity induced in cobalt impurities in iron and the activity of ^{152}Eu induced in rock by thermal neutrons was also measured. Both of these thermal-neutron activities relate to the general neutron fluence but have been difficult to interpret. It is possible that additional measures of neutron fluences can be provided by the counting of neutron-induced fission tracks from uranium impurities in zircons, which are frequently found in soil, brick, tiles, etc.

A few days after the bomb, sulfur was extracted from electrical insulators in Hiroshima out to 1000 m range. The ^{32}P activity was measured by a Lauritsen electroscope. These data have recently been reexamined and reviewed and have been compared with calculations based on a bomb yield of 15 kt and the neutron spectrum calculated to have been emitted. The bomb is assumed to have been tilted by 15° in the direction of aircraft approach. Since the activation is by fast neutrons (approximately 3 MeV) the effects are not axially symmetric and the azimuth of the measurement is relevant. At distances beyond 400 m, the measurement errors were sufficiently large that a clear confirmation of the agreement between the measurements and the calculations could not be obtained. At closer distances, an almost satisfactory agreement was observed. The comparison of these measurements with calculations gives a yield of about 13 kt. Within the accuracy of the measurements, this agrees with the 15 kt accepted in Chapter 2.

It is important to note that the neutron kerma at distances greater than about 1000 m is dominated by source neutrons of energies greater than 1 MeV. Therefore the sulfur activation comparison is important in estimating the uncertainty in neutron kerma at large ranges. The comparison above suggests that calculated neutron kerma with a 15 kt yield at Hiroshima may be 10 to 15% too high, but this is well within the errors of this assay.

In 1967, Hashizume et al measured the activation of ^{59}Co present as a small impurity in steel found in reinforcing bars in concrete buildings and in other uses in buildings. The activation was calculated by Loewe who found it appropriate to calculate directly the activity and compare it with the measurements rather than rely on calibration with a bare reactor source to convert the data to kerma. Loewe found that the calculated activity ranged from one and one-half times that measured at 290 m to one-third times at 1180 m.

To resolve this discrepancy, the contribution of delayed neutrons was calculated. These are only about 1% of the total but are emitted after the explosion when the bomb debris no longer absorbs neutrons significantly. This addition has not yet explained the discrepancy. However, it is noted that the attempt to reproduce test data on thermal neutron activation of gold at Ranger-Fox and Buster-Jangle showed significant discrepancies (see Chapter 3) at ranges less than 1000 m. It appears that further work will be needed before the thermal neutron activation data is understood.

Measurements were also made of the ^{152}Eu activation in rocks. The results show a general correspondence with the calculations, but the experimental (and calculational) uncertainties are too great to permit an accurate evaluation of the neutron fluences.

CHAPTER 6. RADIATION DOSES FROM RESIDUAL RADIOACTIVITY

Fallout of fission products contributed additional irradiation to certain individuals in a few locations. The fallout was measured some weeks or months later and the initial activity could be inferred approximately providing storms had not washed away a large portion of the activity. Another source of irradiation was radioactivity induced in the ground and other materials present in the vicinity of the hypocenter by neutrons from the bombs. Those survivors who entered the area within 1000 m from the hypocenter a few hours or days after the explosions could have received additional radiation from this source. Although it is generally agreed that the direct radiations dominated the radiation doses to survivors, there may have been some survivors who received significant doses from fallout or from induced activity.

Fallout was found in certain restricted localities in Nagasaki (Nishiyama) and in Hiroshima (Koi-Takasu). Based on the usual time dependence, $t^{-1.2}$, the exposure received from one hour after the burst (about the time of the fallout) to infinity can be calculated after fitting to measurements made one or more months after the bomb. The upper limits on absorbed dose from gamma rays for persons continuously in the fallout area at Nagasaki ranged from about 12 to 24 rad. The absorbed doses at Hiroshima ranged from about 0.6 to 2 rad. Since the region of fallout was quite limited, it would appear that the total contribution of fallout to survivor dose was probably negligible in Hiroshima but may have been significant for a limited number of survivors in Nagasaki where an exposure of one-fifth the maximum extends over some 1000 hectares. Estimates of the internal dose from ingested ^{137}Cs are based on whole-body measures of 10 to 13 pCi/kg, yielding about 0.01 rad integrated over 40 years.

The activity in soil and other materials induced by neutron absorption falls off very rapidly with distance from the hypocenter. Exposures near the hypocenter were determined from the known soil analysis and the activities measured at later times. The results at Hiroshima were ^{56}Mn - 26 R; ^{24}Na - 45 R; and ^{46}Sc - 1 R; giving upper limits for absorbed dose of about 50 rad at Hiroshima and about 18 to 24 rad at Nagasaki. The absorbed dose, of course decreases with distance from the hypocenter.

The critical factor in making use of the above estimates of upper limits on absorbed dose from residual radioactivity is to know the history of movement, both the time and position in the fallout or induced field, of the survivor. Some studies have indicated that movement and the shielding by houses reduce the absorbed doses by a factor of two-thirds or more.

At the present time doses due to residual activity are not calculated by the DS86 system. It is recommended that the few individuals from areas of high residual radioactivity not be included in the nonexposed cohort for epidemiological studies.

CHAPTER 7. HOUSE AND TERRAIN SHIELDING

Most survivors of the bombs in Hiroshima and Nagasaki who were close enough to the hypocenter to receive significant radiation doses were shielded in some way from the thermal effects of the bombs. This shielding may have been from a "typical" Japanese house, or by a wall or obstruction, or by terrain. Any shielding gave a reduction in dose compared with the dose received by a person in the open. The procedure used to evaluate the shielding of a typical house or house cluster was:

1. Construct a computer model of a house or house cluster using the best information available about the dimensions and materials of actual houses or house clusters.
2. Using adjoint Monte Carlo techniques, coupled to the free fields, calculate the energy and angular distributions of neutrons and gamma rays at an arbitrary location inside or adjacent to the house cluster.

The technique has been validated by its use on the house and house clusters used in the BREN experiments in Nevada. This validation showed good agreement for gamma-ray measurements with a ^{60}Co source and a variety of house configurations and locations; good agreement for neutron measurements inside houses with a bare reactor source; but poor agreement for gamma rays measured inside houses exposed to the same neutron source. This disagreement is thought to be due to an unsuspected detector sensitivity to neutrons, since the houses were, in fact, exposed to a very intense neutron fluence. Since the neutron-induced gamma-ray component is small, the results were taken to provide adequate confirmation of the technique.

In modeling the Japanese houses there was first a very careful study of the materials in the houses and the peculiarities of the construction leading to nonuniform shielding (as by the roof). Certain features were ignored such as posts and beams.

In analyzing the voluminous results on energy and angular distributions, it was necessary to digest them in terms of kerma transmission factors in order to understand the shielding phenomena. The principal difference between the shielding calculated here and in T65D lies in the gamma-ray shielding. Both the measurements and the calculations of the gamma rays inside a house include the gamma rays produced by neutrons in the materials of the house. This component was considerably reduced by the changes in the neutron spectra introduced in the present reassessment. The gamma-ray transmission factor in T65D was taken to be 0.9. Marcum recognized the problem with the neutron-induced gamma rays and proposed 0.55 for prompt and 0.45 for delayed gamma rays. The present study gives 0.53 for prompt and 0.46 for delayed gamma rays at 1500 m ground range. The neutron transmission factors for houses in T65D averaged 0.32 whereas in this study it averaged 0.38.

The existing computerized files at RERF contain only limited sets of data on the location of shielding elements with respect to a survivor. One of these contains a set of so-called nine parameters. Twenty-one points in the six-house cluster and 40 in the tenement cluster were selected. For each point and for 16 different orientations with respect to the hypocenter, the nine parameters were assigned. This set amounts to 336 plus 640 nine-parameter sets in which each parameter has a frequency of occurrence similar to the actual 10,706 survivors. Only five of the nine parameters (FN, SP, FS, FSS, US; see Chapter 7 for their definitions) appeared to be correlated well with the calculated transmissions. Since FS and FSS are closely correlated, only SP, FS, US, together with FN were used. Finally, all shielding categories were organized according to 3 values of FN, 5 values of SP, and 5 sets of FS and US.

The shielding system then selects all computed cases for a given parameter set and averages the leakage tapes for those cases to give a single leakage tape for each parameter set so that the final shielding system still provides energy- and angle-dependent fluences for each set of parameters.

The "globe shielding" cases were treated by a modified method. First, adjoint calculations were carried out for some 26 locations exterior to a house cluster, 10 locations shielded by a "hill", and for 4 ground ranges, 8 orientations, and 2 cities. For each case, the appropriate "globe" parameters were computed. It was found that a quantity which best correlates with the transmission is the neutron free-field weighted, unblocked fraction of the solid angle (WUBF). Finally, the survivor's WUBF is computed from his globe data and ground range and the best match from precomputed locations is found, which then gives the radiation field for his location and orientation.

Within a given classification in the nine-parameter system, the calculated transmission factors for gamma rays still show a 15 to 20% fractional standard deviation (FSD); but, if not subdivided by the nine parameters, the FSD for gamma rays would be 30%. The FSD for neutrons is similar.

CHAPTER 8. ORGAN DOSIMETRY

In order to make the maximum use of the information on each survivor, the actual dose delivered to each relevant organ is being calculated. This information will be processed together with the shielding data in the new dosimetry system being made available at RERF. The determination of dose at the site of any organ involves the following steps.

1. Selecting a phantom or calculational model appropriate for typical young and adult Japanese in the year 1945.
2. A calculational methodology to compute energy and angular distributions for neutrons and gamma rays at an appropriate location in the phantom for the proper location of the survivor.
3. Determination of the kerma from the fluence and some aspects of the detailed structure of the organ.
4. Verification and validation by comparison with experiment and other calculations.

For wartime Japanese, the nearest existing phantom was that of a 57 kg person. This was modified in certain dimensions and organs to best approximate adult Japanese of 1945. The same basic phantom was used for both males and females. For small children aged less than 3 years a 9.7 kg phantom was used whereas for ages between 3 and 12 years a 19.8 kg phantom was used. The sitting or kneeling posture was represented by appropriately bending at the hips and knees and extending arms at 45° to the trunk.

The method of calculation is the same as that used for the shielding calculations. An adjoint calculation of the radiation transfer through the phantom to the organ in question can be coupled to the appropriate energy- and angle-dependent fluence in the house to give the energy- and angle-dependent fluence at the organ site. Using 30,000 particle histories about 5% precision in kerma can be achieved. With 400,000 histories, precision in kerma better than 1% is possible. In the final system, 6,000 histories are needed per organ to calculate dose and about 40,000 histories to calculate the spectrum.

The kerma in an organ is calculated using the detailed organ description in Appendixes 8-1 and 8-2. The final quantity desired is the absorbed dose to the organ. With one exception, the conditions for charged-particle equilibrium are met in the organs considered, and the absorbed dose can be equated to the kerma (see Editor's Note). The exception is the bone marrow; charged-particle equilibrium does not exist and special calculations of the absorbed dose were made for the bone marrow (Appendix 8-4).

The organ dose system applied to phantoms has been compared with experiments for isotropically incident gamma rays with very good agreement. For exposure to a mixed field of neutrons and gamma rays, the neutron measurements show good agreement as do the transmission factors for incident gamma rays. However the gamma rays resulting from neutron interactions in the body show a much larger measured than calculated result. This discrepancy is reminiscent of the discrepancy in the BREN house shielding measurements and suggests either a problem in neutron sensitivity of the gamma-ray detectors or a fundamental problem in the calculations. A simple phantom was exposed to reactor neutrons and compared to calculations. The agreement was generally within 10% except for the epithermal and thermal neutrons where the discrepancies were larger. In general, there is agreement in other experiments to within about 10%. The average organ transmission factor resulting from these calculations was considerably increased compared to T65D (compensating in large part the reduced gamma-ray transmission factor of houses).

The sensitivity of the organ dosimetry to changes in the various parameters of the phantom and its posture was examined; and, in addition, the uncertainty of the organ dose to be ascribed to the corresponding uncertainties in the parameters was calculated. It was concluded that phantom uncertainties contribute 10 to 20% in dose uncertainty; the uncertainty depends significantly on phantom orientation; the uncertainty also varies significantly with dose component, with organ depth, and with house shielding for some organs.

The organ dosimetry system calculates the kerma from the energy-differential neutron and gamma-ray fluences in each organ of interest. The system accomplishes this by storing 6,000 particle histories for each organ in each of three phantoms in two different postures. When requested, the system can provide the energy-dependent fluence in any organ or the absorbed dose in an array of organ subvolumes, but this much detail requires 40,000 histories per organ and the system is eight times slower. The organs chosen for dosimetry in DS86 are as follows: active marrow, bladder, bone, brain, breast, eye, fetus/uterus, large intestine, liver, lung, ovary, pancreas, stomach, testes, and thyroid.

CHAPTER 9. DOSIMETRY SYSTEM 1986

This chapter describes the computerized Dosimetry System 1986 (DS86), for calculating the organ doses received by A-bomb survivors. DS86 incorporates state-of-the-art computations and models describing the yield and radiation output of the bombs, the free-field radiation environment, the shielding by Japanese houses and "globe" cases, and the body shielding to the various organs.

DS86 is designed as a modular system, encompassing separate data bases for each of the free-field radiation components, for each of several distinct shielding environments, and for each of many different organs.

The free-field components consist of the prompt neutrons, the early gamma rays (prompt fission gamma rays and gamma rays from inelastic scattering and capture of prompt neutrons), the late gamma rays (from fission products and from delayed neutrons), and the delayed neutrons. A new or revised treatment of any of these components can readily be introduced by appropriately substituting a new data base for the old one.

The shielding data bases include, at present, models for all survivors with nine-parameter shielding and all survivors with globe-data shielding descriptions. It is intended to add a module to describe factory shielding later in 1987.

Uncertainties were estimated for the shielding and organ environments by calculating the fractional standard deviation among the many shielding and phantom environments that had been computed. These were combined with estimated uncertainties in the free-field radiation fluences to provide a preliminary estimate of uncertainty in the computed doses. This part of the system, however, is incomplete at present and will be finalized only after an overall uncertainty analysis.

The DS86 system is based on the present status of dosimetry as described in Chapters 1 to 8 of this report. As new knowledge or data become available in the future, revision may become necessary, but no major changes are expected.

DS86 was reviewed by the Japanese and US oversight committees on 16 and 17 March 1986 and recommended for use at RERF. It was adopted by RERF shortly after and is now being used in the estimation of radiation dose to survivors.

UNCERTAINTY ANALYSIS

It is planned to provide a thorough discussion of errors, uncertainty, and sensitivity in a future report. This analysis has not yet been carried out except in parts.

Only the uncertainties in yield, bomb source output, and transport in air have been estimated up to now. These estimates lead to an estimated uncertainty in the free-field kerma, not including the direct measurements of activation and TL dosimetry, of perhaps 25 to 30%. The direct measurement of sulfur activation may be able to reduce the uncertainty in neutron dose. The direct measurement of gamma rays by TL dosimetry, particularly in the 1000 to 1500 m range, should considerably reduce the uncertainty in the free-field kerma, which is dominated by the gamma rays, to perhaps 10 to 15%.

The uncertainty in final organ doses will probably arise mostly from uncertainty in shielding, in location of the survivor, and in orientation in the shielded environments. This type of uncertainty has been estimated by extensive calculation of many possible shielding environments, and their resulting doses, that are compatible with the limited information available in the coded files on nine parameters, house construction details, and other significant details of the environment. The results of this type of uncertainty are discussed at some length in Chapters 7 and 8, but they are not yet codified in the dosimetry system.