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William H Ellett, Editor

Panel on Reassessment of A-bomb Dosimetry, Chairman, Frederick Seitz
Advisory Committee on the Radiation Effects Research Foundation
Commission on Life Sciences
National Research Council

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Members of the United States and Japan Working Groups in the Binational Collaborative Study

PREFACE

In 1981 the Department of Energy (DoE) undertook a reassessment of the radiation doses received by A-bomb survivors at Hiroshima and Nagasaki. As part of this reassessment, the National Research Council was asked to establish an expert panel that, in concert with a corresponding Japanese panel, would provide an ongoing review of a new dosimetry system to be developed by DoE National Laboratories, contractors of the DoE and the Department of Defense, and Japanese scientific groups.

This report was prepared by the Panel on Reassessment of A-bomb Dosimetry, chaired by Dr. Frederick Seitz, which was assembled by the Advisory Committee on the Radiation Effects Research Foundation (RERF) of the Research Council's Commission on Life Sciences. The panel's purpose was to provide oversight of the dose reassessment so that the new dosimetry would be complete, state of the art, and meet the needs of the Radiation Effects Research Foundation in carrying out its studies on the health status of A-bomb survivors.

The Radiation Effects Research Foundation is a binational organization, and the dose reassessment was from the beginning a collaborative study between U.S. and Japanese scientists. A parallel Senior Committee chaired by Professor Eizo Tajima was established by the Japanese Ministry of Health and Welfare, and the panel gratefully acknowledges the cooperation it received from its Japanese counterpart. The panel also acknowledges the careful typing and proofreading of this report by Ms. Doris Taylor and Mrs. Catherine Berkley.

I. Introduction and Background

Reliable estimates of the doses received by the A-bomb survivors are essential for the quantitative understanding of the survivors' medical experiences, and particularly for the estimation of the risk of cancer per unit dose. Initial reports on A-bomb casualties and later on the delayed effects of radiation were in terms of the distance between the hypocenter of the explosions and survivors. However, the need for quantitative dose estimates was recognized from the beginning. Tentative estimates of the dose in air at various distances, designated T57, and somewhat later estimates of the dose to individual survivors, T65D, were developed by the Atomic Bomb Casualty Commission (ABCC) and the Oak Ridge National Laboratory (ORNL).[1] The T65D dose estimates were used in the 6th report on the ABCC Life Span Study published in 1971[3], which became the basis of most of the risk estimates in the initial BEIR report[7] and has continued to be the dosimetric basis for subsequent studies of radiation risks[8,15] including Life Span Study Report 10, now in press.[10] The T65D estimates are now being replaced, but they have had a long and useful life that amply justifies the considerable intellectual and financial effort that went into their development.

T65D estimates were largely based on empirical observations at atomic weapons tests and large-scale experiments carried out by ORNL with a nuclear reactor and ^{60}Co source. In order to implement the results obtained in the experiments, detailed shielding histories of the A-bomb survivors were obtained by interview. These histories contain information on the survivors' locations and shielding circumstances at the time of the bombings; information that was parameterized and serves as one of the foundation stones for the present dose reassessment.

Although the T65D estimates have been used for more than 20 years, it became apparent by 1980 that they were probably more accurate for survivors in Nagasaki than in Hiroshima. This is because of differences between the weapons used in each city. The Nagasaki bomb was an implosion device similar in many ways to the bombs exploded at weapons tests, information from which was used in developing the T65D system. The Hiroshima bomb was never tested. It was a one-of-a-kind device in which a part of the fissionable material was fired into the remainder which was surrounded by a large amount of iron and other heavy elements. Calculations at Los Alamos in 1976 indicated that due to the iron, the neutron energy spectrum from this bomb was quite different from the neutron spectrum for ^{235}U fission assumed in the development of T65D. Subsequently, investigations at ORNL and the Lawrence Livermore National Laboratory (LLNL) showed that estimates of the neutron kerma from the Hiroshima weapon were significantly different than that estimated in the T65D system.[5,6]

Preliminary work by a number of investigators who were interested in the problem was reported at a symposium conducted by the Radiation Research Society in May 1981.[14] This was followed by a Department of Energy symposium, Reevaluation of Dosimetric Factors: Hiroshima and Nagasaki, September 15-16, 1981. The reports at this symposium made it clear that a thorough reassessment of the A-bomb dosimetry was warranted.[2] The Department formed an informal working group of DoE contractors and National Laboratory personnel to develop a new dosimetry system for estimating doses to A-bomb survivors. Professor Robert Christy, California Institute of Technology, chaired this working group. Concurrently, the National Research Council of the National Academy of Sciences was asked to form an oversight panel to provide advice and an ongoing review of the working group's efforts. This panel is chaired by Dr. Frederick Seitz, President Emeritus of Rockefeller University and a former President of the Academy.

The panel met for the first time on July 21, 1982 and over the next 4 years had nine additional meetings, several of which were joint meetings with Professor Christy and members of his working group, who briefed the panel on various phases of their investigations. These meetings were valuable to each side as the panel was often able to provide advice on what information is required by the RERF for its studies, e.g., the list of organs for which dose estimates are needed.

Dr. Seitz and key panel members attended dose reassessment workshops in Japan[11,12] and the panel hosted the third binational workshop in Pasadena, California on March 12-14, 1985 at which the plan of the final binational report was developed. In addition, panel members attended special workshops in Hiroshima and Salt Lake City, Utah on the development of a retrospective thermal luminescent dosimetry to assess the gamma-ray doses in each city.

A major task for this panel has been the review of the report on the binational collaborative study, "US-Japan Joint Reassessment of Atomic Bomb Dosimetry in Hiroshima and Nagasaki. Final Report."[13] First drafts of the Final Report were reviewed prior to the "Fourth Joint Workshop on the Reassessment of Atomic Bomb Radiation Dosimetry" held in Hiroshima on March 16-17, 1986. A fully edited penultimate draft was reviewed by the panel in September and October of 1986. Both the panel and the Japanese Senior Committee provided written comments on this draft. The panel also discussed its views with Dr. Robert Christy, Chairman of the DoE Working Group, at their meeting on November 3, 1986. Final comments arising from this meeting were forwarded to the editor of the binational report, Dr. William Roesch, a former member of the panel. In this regard, the panel would like to thank the authors of the binational report and Dr. Roesch for the close attention given to their comments and their willingness to revise the report along the lines suggested by panel members.

It is not the intention of the panel to duplicate the material, even in summary, contained in the binational report, which is in press. Rather, the purpose of the panel's report is to address how well the binational study answered the need for a reassessment of the A-bomb dosimetry, pointing out the strengths and weaknesses of the models, methodologies, and documentation prepared by the DoE and Japanese investigators. Finally, the panel presents some recommendations concerning the future of these studies.

II. The Transport of Radiation Due to Nuclear Explosions

When a nuclear weapon is detonated, energetic neutrons and gamma radiation escape from the extremely high temperature mass of what were once bomb components. These are called prompt gamma rays and neutrons. The neutrons are important for two reasons. They produce large amounts of gamma radiation by secondary processes (also part of the prompt component) and, depending on the type of weapon, can themselves be an important source of exposure. In the case of the A-bombs used in Japan, neutrons were largely attenuated by the materials in the weapons themselves but with an important difference between the Hiroshima and Nagasaki bombs. The Nagasaki weapon was an implosion device in which the fissionable material was compressed by a large mass of chemical explosives. The hydrogen, and to some extent the nitrogen in the explosives, moderated escaping neutrons so that they were absorbed in air relatively close to the bomb. In this capture process, high-energy prompt gamma rays were emitted which produced about 40 percent of the dose received by survivors. The Hiroshima weapon was a so-called gun barrel device which contained a large amount of iron and other heavy elements. The iron partially attenuated the escaping neutrons by reducing their energy but to a much lesser extent than was the case at Nagasaki. The ultimate fate of these neutrons was mainly capture by nitrogen in air with the production of prompt secondary gamma rays. However, unlike the situation at Nagasaki, many more energetic neutrons escaped and the dose due to neutrons at Hiroshima was about twice that at Nagasaki.

As important as neutrons are in terms of direct radiation and as producers of prompt secondary gamma rays, it is noteworthy that most of the gamma dose received by the survivors was from delayed radiation produced by radioactive fission products within the fireball. These radionuclides undergo radioactive decay with the emission of neutrons, beta particles, and gamma rays. The fireball rises, like a hot air balloon, so that after a few seconds the debris is too far above ground level to be an important source of exposure to the survivors. However, in some cases, deposition of large particles by gravitational settling or scavenging of the radioactive debris by precipitation can result in significant ground deposition, i.e., fallout. This occurred to a very limited extent in small regions of both cities.

Because the fireball is a moving source whose strength decreases rapidly with time, the calculational approach used in the dose reassessment treated the delayed gamma radiation in a somewhat different fashion than the prompt neutrons and secondary gamma radiation. However, the essential feature of the mathematical treatment of the radiation transport in both cases is that angular scattering and energy degradation are accounted for so that the radiation field at survivor locations is fully defined. Given information on the number, direction, and energy of the neutrons and gamma rays, the dose at various locations near ground level can be readily calculated.

Such free-in-air (FIA) doses, more exactly the kerma* within a small tissue sample in air, do not, on their own, describe the doses to

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*kerma - kinetic energy released in material, dE_{tr}/dm.

survivors. Most of the survivors who received appreciable doses were inside structures or otherwise shielded from the bomb blast and thermal pulse. The absorption and scattering of radiation caused by structures can be accounted for by means of adjoint Monte Carlo calculations in which the paths and interactions of a large number of gamma rays and neutrons are traced. This provides a data base on the radiation field within houses at positions where survivors were located. Similarly, the body itself provides significant self shielding to the underlying organs, the amount depending on the organ location and the survivor's orientation relative to the direction of the radiation. Again, adjoint Monte Carlo calculations can be used to estimate the amount and spectral distribution of the radiation reaching each survivor's internal organs and hence the dose to these tissues.

III. Adequacy of the Dose Reassessment

It is convenient to discuss the adequacy of the dose reassessment in terms of its component parts as described in the binational report.[13] The order of the topics considered here is the same as the chapter sequence in "US-Japan Joint Reassessment of Atomic Bomb Radiation Dosimetry in Hiroshima and Nagasaki. Final Report." Readers who are unfamiliar with that report may refer to Appendix I, in which the Executive Summary of the Final Report is reproduced.

1. Estimates of Bomb Yield

Although commonly expressed in kilotons of TNT, bomb yield is actually a measure of the energy release and hence is proportional to the number of fissions which occurred in the weapon. This number governs both the amount of radioactivity in the fireball and the number of neutrons and initial gammas produced in the nuclear explosion. The accuracy and precision of the yield estimates therefore is a determining factor in the usefulness of the final dose estimates for, survivors.

Yields of three bombs, for practical purposes identical to the Nagasaki bomb, were measured at weapons tests. The results at these tests were consistent, the yields ranging from 20.3 to 21.7 kt. At the two tests where different measurement methods were used to determine yield, results differed by no more than 1 kt. Considerably less precise estimates based on field observations at Nagasaki are consistent with the weapons test data as is also the calculated design yield, 22 kt.

o The panel believes the estimate of the yield for the Nagasaki bomb given in the binational report, 21 ± 2 kt is reliable. Given that the listed uncertainty in the yield is said to correspond to 2.3 standard deviations, it is a remarkably precise one as well.

The Hiroshima bomb was not tested and data obtained at the time of the explosion show considerable variation. One way of estimating the Hiroshima yield is by comparing collateral blast and thermal damage in the two cities and scaling the results to the 21 kt yield estimated for Nagasaki. Such a procedure assumes that the fraction of the fission energy going into heat, blast, and initial radiation for the two weapons was the same. In view of the difference in construction of the two bombs, this is a critical assumption that cannot be directly verified. On the average, such relative measures give estimated yields at Hiroshima of 14 kt and 15 kt for thermal and blast effects, respectively. This is consistent with direct measures of the yield based on induced radioactivity from fast neutrons, thermoluminescence due to gamma radiation, thermal damage, etc. Again these methods are not very precise, such estimates ranging from 12 to 18 kt.

After weighting each of the estimates of the yield in proportion to its apparent reliability and averaging, the investigators concluded that the yield of the Hiroshima weapon was 15 ± 3 kt.

o The panel believes this estimate is as good as can be obtained and that the listed uncertainty is neither unduly optimistic nor pessimistic. The panel recognizes it would be desirable to increase the accuracy with which the yield of the Hiroshima weapon is known, but has no advice at this time on how to do so.

2. Source Terms

The binational report contains a full description of the leakage spectra from the Hiroshima and Nagasaki weapons, based on computer models that include a full hydrodynamic treatment of the weapons as they exploded. The resultant neutron and gamma leakage spectra are tabulated so that results are available to others who may want to calculate the energy transport. The Nagasaki weapon had many more low-energy neutrons below 10 keV than was the case at Hiroshima, but fewer neutrons at higher energies. The shape of the new neutron leakage spectrum for the Hiroshima bomb, as recalculated in cylindrical geometry, does not differ much from the earlier one-dimensional calculations by Preeg.[9] However, the newly calculated gamma-ray leakage spectra are significantly different, primarily due to changes in gamma-ray cross-section data. Use of a two-dimensional calculation for the Hiroshima bomb documents the high degree of azimuthal asymmetry of the initial radiations from that weapon due to its cylindrical geometry.

Several studies were made by the DoE investigators to verify the accuracy of the methodology used to calculate leakage spectra from the Hiroshima and Nagasaki weapons. A variety of neutron sources were used in these tests. Comparisons were made between calculations and the measured kerma at the BREN and Aberdeen (APRD) reactors and with measurements at three weapons tests. Such comparisons are for the combined effects of leakage spectra and air-transport. Nevertheless, they increase confidence in the source-term calculations for the two weapons.

The Nagasaki weapon was approximately spherically symmetric and was similar enough to tested weapons that the accuracy of the source-term calculations was not a cause of concern. Because the Hiroshima bomb had unique characteristics, Los Alamos National Laboratory set up and loaded a replica which permitted tests of the neutron emissions when operated as a controlled critical assembly. Although the replica could not duplicate thermal motion at the moment of explosion, the panel believes it provided credible tests of the methodology used to calculate the neutron spectrum from the Hiroshima bomb.

An important set of measurements made with the replica was of the criticality configuration, the distance between components at which the assembly becomes delayed critical, a parameter which places an upper limit on bomb yield. This test was found to give a maximum yield of 17 kt.

The most important verification of the source term was made by comparing calculated and measured neutron fluences as determined from sulfur activation by high energy neutrons when the replica was operated as a low-power reactor. These measurements agree well with calculations for the neutrons emerging from the "waist" of the weapon but initially not at the nose. However, measurements and calculations were later reconciled reasonably well for radiation emerging from the nose as well.

The panel notes that the possible effect of premature breakup of the weapon was considered and this possibility has been dismissed because the duration of the disassembly process is too short to allow propagation of a mechanical shock wave.

o In general, the measurements at the replica constitute strong evidence that the source leakage spectra have been calculated correctly. The report indicates that the standard deviation of the calculated source term is about ±20 percent. Replicate calculations using recent revisions in the iron cross-section indicated little change, a 1-percent increase in high-energy neutrons. The panel believes that the calculated source terms are as good as can be provided at this time and have been tested to the extent possible.

- Neutrons having energies greater than 1 MeV that emerge from the Hiroshima weapon are important because they determine the neutron dose at 1 kilometer or more. The panel believes that the uncertainty in the spectrum of these neutrons should be given further attention.

3. Radiation Transport

The binational report presents a comprehensive study of how the radiation field varied with distance from the point of explosion to where survivors were located. Considerable emphasis is placed on the comparison of results using different models of radiation transport and various input parameters, e.g., ground composition. This strengthens the conclusion that the results are robust. Examples of these comparisons and tests are:

(1) ORNL discrete ordinate calculations versus LLNL Monte Carlo calculations.

(2) Measured and calculated delayed gamma exposure versus time at Shot Hood.

(3) Measured and calculated thermal-neutron fluence at weapons tests Ranger Fox and Buster Dog.

(4) Measured and calculated gamma-ray exposure at the Ranger Fox and Buster Dog nuclear tests.

(5) Science Applications International Corporation (SAIC) versus LLNL calculations for gamma and neutron FIA kerma.

(6) Comparisons of calculated delay gamma rays as a function of time with the results of laboratory measurements.

(7) Sensitivity of ^{32}S activation, ^{59}Co activation, and FIA kerma to humidity and air-ground interface.

(8) Sensitivity of FIA kerma to perturbed and uniform air distributions.

The report reviews the determination of epicenters at the two detonations and summarizes the available information on meteorology and ground composition.

o The panel believes that given the historical nature of these investigations, these data are as complete as can be expected.

The main discussion is devoted to the transport of prompt and delayed radiation. The amount of moisture in the air and the effects of ground scattering are taken into account in the transport calculations. The two-dimensional discrete ordinate calculations of prompt radiation transport performed at ORNL are discussed in detail. This includes the generation of appropriate cross-section sets, testing for anomalous effects due to the structure of the calculational model, and the choice of response function. The LLNL Monte Carlo calculations are then discussed in similar detail. Comparisons with ORNL calculations indicate that point estimates of kerma with the two types of calculations agree to within 10 to 15 percent over distances ranging from 50 to 1,950 meters.

The report discusses the SAIC calculation of debris gamma radiation from the fireball. The choice of time-dependent source terms for the fission products from each bomb is justified. Hydrodynamic effects are accounted for by taking snapshots of air density at various times and equating one-dimensional transport through these configurations with one-dimensional transport through uniform air of the same ρR (g/cm^2) value, an approximate but reasonable solution. An adjoint Monte Carlo Code, is used to calculate effects introduced by the ground so that the one-dimensional transport results can be applied to this two-dimensional exposure situation. To test this methodology, calculations of gamma-ray kerma versus time are compared with measured values at Shot Hood.

o The panel believes the agreement is satisfactory.

Delayed neutrons are approximated by Maxwellian energy distributions for each half-life group. Transport modeling procedures were tested by comparisons with measured values of thermal-neutron fluence at weapons tests. The report shows that at distances greater than 1 km the importance of neutrons to the FIA tissue kerma is limited to source neutrons above about 1 MeV.

Finally, tabulations of the FIA tissue kerma are provided for the combined prompt and delayed neutrons and gamma rays for each of the two cities. The various components of the new neutron and gamma FIA tissue kerma are also plotted and compared with T65D kermas. Lastly, comparisons are made with earlier calculations by W. Loewe at LLNL.

o The panel believes the treatment of radiation transport was very thorough. Not only were many comparisons between calculational models made but the same transport models were used to calculate the kerma at instrumented weapons tests. Comparisons of calculated kermas with the data from weapon tests indicate that the major features of the radiation transport are well understood and adequately accounted for in calculations. However, the binational report contains little information on the uncertainty of the transport calculations and how this changes with distance. The panel believes the anticipated uncertainty analysis should include this information.

4. Verification of Calculated Gamma-Ray Kerma

The calculations of gamma-ray kerma were validated by means of thermoluminescent (TL) dosimetry. This methodology has much in common with the TL dating of archaeological objects: extraction of quartz grains from the tile or brick specimens, measurement of the "glow curve" by one of several procedures developed in TL archaeometry, calibration of the sensitivity of the quartz by administering a known dose in the laboratory, determination of the background (non-bomb) radiation exposure *via* subsidiary measurements, and interpretation of the experimental data.

Although TL dosimetry is simple in principle, the investigators recognized that its constituent operations involve a number of assumptions which must be carefully checked. The same is true for the several different TL measurement procedures that have been devised for applications to the problem. The report shows that care has been taken to deal with these matters, although not all of the questions have been resolved. Both the "high temperature" quartz inclusion and the "predose" procedures were used in the investigations. The manipulations and theory associated with the more sensitive "predose" technique are considerably more complex than those of the high temperature technique. This introduces additional assumptions and complicates the analysis of the measured doses. One of the strengths of the report is that it clearly demonstrates both the power and the limitations of A-bomb TL dosimetry by a detailed discussion of all the techniques used in the project and by the tabulations of results from the participating laboratories.

Retrospective A-bomb dosimetry is constrained to work with a "natural" phosphor, quartz, which is about 10^{-4} as efficient as the best synthetic TL phosphors and may vary appreciably in properties from grain to grain. The quartz must be extracted from the tile or brick by a sequence of steps which varies from laboratory to laboratory, starting always with mechanical crushing of the specimen followed by some combination of magnetic separation, ultrasonic cleaning, sieving, chemical dissolution of silicates in acids, etching of the quartz in hydrofluoric acid, washing with water and other solvents, and drying. It is assumed, but not always checked by independent observations (cathodoluminescence tests or x-ray diffraction), that the end product is indeed uncontaminated by other solids. A case of the contamination of supposedly pure quartz extract by the silicate mineral plagioclase is described in the report, as well as the anomalous TL behavior of samples containing this impurity.

A typical yield of quartz extracted from tile is one part in 10^4 (100 mg quartz/kg tile) and from brick about two to three times as much. The quartz samples used in the American and British laboratories were about 2.5 mg, whereas at least one of the Japanese laboratories used 15-25 mg samples. Since less homogeneity exists with natural material than with synthetic phosphors, one would expect a greater scatter of results with the smaller sample sizes. This scatter could obscure an effect of potential importance.

Practitioners of TL archaeometry believe that they can date artifacts with an error of somewhat less than 10 percent. From the data contained in the present report it may be concluded that the additional complications in the dose reassessment (including the need for good estimates of the background dose) increase the uncertainty of the results to ±15-20 percent for doses of 100 rads or more, ±50 percent for doses of 20 rads, and about 100 percent for doses of 10 rads, which is probably the lower limit of reliable detection even by the "predose" technique.

It would have been better if the samples available to the American and British investigators had been from a variety of locations in each city rather than from a single location in each. A broader distribution of samples could have provided further insights. However, the general agreement between all laboratories on the doses at these locations is within the limits of error mentioned above.

The TL data from Hiroshima University and the Ieno Wall at Nagasaki are the strongest physical evidence for preferring the DS86 calculations over T65D. Even so, in some, but not all, sets of measurements at Hiroshima University the dose estimates based on measured TL values and the calculated doses differ by twice the estimated uncertainty. While this may be due to a systematic error in all the Hiroshima University TL dose determinations, or some unidentified causes that make the dose at this location unrepresentative of the doses elsewhere, it is more likely that the analysis of the uncertainty in the DS86 calculations will show that DS86 and the TL data overlap within the limits of error of both approaches.

o The panel believes the TL investigations were state of the art and basically confirm the calculational models of gamma-ray transport in DS86. However, these measurements on "natural" materials are not and cannot be very precise. The uncertainty in the measured values indicates that they should be viewed as supporting evidence and not as a source of empirical correction factors for the calculated gamma-ray doses.

5. Verification of Neutron Fluence Calculations

One of the major tasks in the dose reassessment has been to test the calculated doses to the extent feasible. Except for the TL measurement described above, almost all of the relevant measurements were performed 20 or more years ago so that evaluation of the experimental evidence is not an easy task. Under these circumstances it is not surprising that confirmation of neutron fluence has been only partially successful, excellent for fast neutrons, poor for slow neutrons.

The two major sources of data for verification of neutron kerma estimates are ^{31}S, ^{32}P transformation induced by fast neutrons and ^{59}Co, ^{60}Co transformation by slow neutrons. The former data were considered to be too inconsistent for use in the formulation of the T65D dosimetry system. However, the newer calculational methods used in the reassessment, which take into account the asymmetry in the initial direction of the source neutrons, show that these data confirm the calculated number fluence of high-energy neutrons. Validity can be confirmed only out to about 600 meters from ground zero. Beyond this distance, the uncertainties in the data are too large to allow a meaningful comparison between the measured and calculated activation.

Epithermal (keV) neutron fluences at two locations at Nagasaki and four locations at Hiroshima were estimated by measuring induced cobalt-60 activity in iron reinforcement bars embedded in concrete structures. These low energy neutrons which become thermalized in the concrete are an indirect measure of the fast neutron kerma at locations somewhat closer to the source. Although the slow neutron kerma is too small to make a significant contribution to the dose received by survivors, an ability to predict the variation of epithermal neutrons with distance would give additional credence to the neutron transport calculations.

However, the report shows poor agreement between calculated and measured ^{60}Co activity at the four locations where iron samples were collected in Hiroshima. The essential feature of this disagreement is that the calculated mean free path of slow neutrons is substantially less than measured so that the differences increase with distance from ground zero. Both the calculations and data appear to be robust. The report indicates that the calculational results are not very sensitive to the assumed ground composition, hydrodynamic variations in the air, or within realistic limits the amount of boron in the concrete.

Three possible explanations are offered for this discrepancy:

(1) Unknown causes invalidate the cobalt activation data.

(2) Calculations of neutron fluence at high energies are good but those at low energies are bad.

(3) Calculated neutron fluences are in error by factors of 3 or greater.

A fourth possibility which might be considered part of (3) is:

(4) Calculated neutron fluences are in error because the high-energy tail of the neutron-leakage spectrum from the Hiroshima weapon has been calculated incorrectly.

The discrepancy between the ^{60}Co measurements at Hiroshima and calculations has been verified by Kaul and his colleagues at SAIC. It is of interest that more recent information than described in the binational report indicates that a similar discrepancy initially observed in the ^{60}Co data from Nagasaki has been removed by means of 1-D calculations which use much smaller neutron energy and spatial intervals than is possible with the 2-D calculations used to prepare the data in the binational report.[4] This technique does not, however, do much to remove the discrepancy at Hiroshima, which remains unresolved.

While measurements of thermal activation of europium are discussed in the binational report, the conclusion is that although the measurements do not disagree with calculated europium activation, the uncertainty in the measurements is too great to have much bearing on the observed ^{60}Co discrepancy. Unlike the ^{60}Co results at Hiroshima, comparison of measured and calculated gold activation at the Ranger Fox test add further credence to the accuracy of the calculational approach used in the dose reassessment. This issue has not been settled. It is possible that thermal-neutron activation of uranium in glass or mineral specimens may provide an opportunity for additional comparisons in the future.

o On the basis of the lack of agreement between measured and calculated ^{60}Co activation, the binational report concludes that the "neutron doses carry doubt until further work is done." What is missing in this discussion in the report is a quantitative estimate of the uncertainty of the calculated FIA neutron kerma. The panel recommends that the uncertainty analysis of the dose reassessment, now in preparation at ORNL, provide detailed information on this point. The panel has however been impressed by the thoughtfulness with which the experimental tests of the calculated neutron kermas have been addressed.

6. Residual Radiation

One of the objectives of the dose reassessment has been to assemble in one place a compilation of data on residual radiation due to soil activation and fallout in the two cities. Much of this information was obtained by Japanese scientists shortly after the bombings in 1945 and has not been readily available to others. The chapter on residual radiation in the binational report goes well beyond data collection and provides an objective evaluation of the early measurements, and in the case of neutron activation, comparisons with recently calculated values of soil activation. The report illustrates how variable the data on soil composition is and how this influences the calculated exposures due to neutron activation. However, the important activation products in soil are identified and the exposure as a function of time after bombing is calculated based on the half-lives of the identified elements. As expected, the estimated exposures are very dependent on the assumed re-entry time of survivors and, to a lesser extent, the duration of their exposure. The agreement between current calculations of exposures and exposures measured in 1945 is reasonably good.

Fallout occurred in both cities in places about 3 kilometers from ground zero. In the case of Hiroshima the area affected is rather small, as are the estimated doses, a few hundreths of a gray at most. In the case of Nagasaki, a district on the outskirts of town, Nishiyama, received significant fallout. Exposure within this area (a few hectares) was quite variable, depending on location and the duration of exposure. Relevant U.S. and Japanese data from this location are included in the report. It is possible that the dose to internal organs due to residual radiation at this location could be 0.1 Gy or more. Doses due to prompt and delayed radiations near Nishiyama are so low that the survivors would be considered unexposed or nearly so. The report concludes that persons living where fallout occurred should be excluded from epidemiological studies because of uncertainty in their true organ doses, a conclusion with which the panel concurs.

o The panel believes that the reassessment of dose due to residual radiation is thorough and as complete as possible given the quality and quantity of information available today.

7. House and Terrain Shielding

One of the major improvements brought about by the dose reassessment is a better understanding of the shielding provided by structures in the two cities. The protection provided by shielding was seriously underestimated with T65D dosimetry and the new information has a significant effect on the estimated doses. Blast and thermal effects in the two cities were extensive. Almost all survivors who received significant doses were shielded by structures. The reassessment does not include survivors in concrete buildings or at other locations where the dose depends critically on the details of the survivor's location with regard to openings in the buildings, e.g., windows. The panel concurs with this limitation; poorly estimated doses do not contribute to the understanding of radiation effects but rather tend to obscure the better data. To date the dose reassessment has been mainly concerned with typical Japanese housing including tenements. It does not treat single structures but rather clusters of houses, as is truly appropriate for Japanese cities.

House plans and the arrangement of houses in typical clusters were taken from the detailed histories of survivors in RERF files. Very careful attention was paid in the reassessment to the shielding properties of the materials used in pre-war Japanese homes and the details of house construction. This information was incorporated into the modeling used to estimate the fluence at survivor locations after perturbation by the surrounding walls and roofs of the house and cluster. A number of sensitivity analyses were formed to test the assumptions made in the modeling.

Verification of the calculational models were made by applying the codes to shielding measurements at weapons tests and the BREN and gamma-ray experiments used for the development of T65D. The calculational model is reported to have performed well in predicting measurements at weapon tests where replicas of Japanese houses were exposed. They were also successful for the case of BREN neutrons and cobalt-60 gamma rays, but the shielding calculations have not been able to validate the measured shielding factors for secondary gamma rays in the BREN experiments. The reason for this failure is not understood even though it has been studied in detail. The major change in house-shielding estimates resulting from the reassessment is for gamma-ray transmission. For example, the reassessment gives about 50 percent while T65D yields 90 percent.

The actual application of the shielding data was indirect and this may, to some extent, degrade the validity of the estimated doses. Under T65D, the house-shielding information was coded for each survivor in terms of nine parameters, only four of which were shown in the dose reassessment to be independently correlated with fluence at that location. Fluence calculations are made in terms of the limited information contained in these four parameters and the distance of the survivor from ground zero. Unfortunately, verification of the adequacy of this approach, by comparing fluence estimates based on the four parameters to benchmark calculations based on the full shielding history, has not been completed.

o The panel views such verification as essential and believes it should be fully incorporated into the uncertainty analysis now under way at ORNL. Aside from this important point, the panel believes the work on structural shielding is first class and that it should be extended to include survivors shielded by terrain and by lightweight structures other than domestic houses. Its extension to buildings with heavy equipment or thick walls is probably not warranted.

8. Estimation of Organ Dose

The desired end result of the dose reassessment is reliable estimates of the doses delivered to the various organs within a specified survivor. This aspect of the reassessment was performed with particular care. First, information was gathered on body size of Japanese of each sex at various ages during the period of interest, a welcome departure from assuming a 70 kg male. Three anthropomorphic models were selected; adult, child, and infant. Since about two-thirds of the adult survivors were female it is surprising that the adult model is based on the larger male, an unnecessary, even though relatively unimportant source of bias. Several different postures e.g., standing, kneeling, etc., are considered in applying these models. Because the dose to some organs, e.g., the breast, varies considerably depending on the orientation of the survivor relative to line of sight to the weapon, a special effort was undertaken by RERF to recover this information from the survivor shielding history and incorporate it into the new system for calculating organ doses.

As was the case for structural shielding, adjoint Monte Carlo calculations were used to estimate the energy fluence and dose at various locations with the body. Appropriate analyses of changes in the dose

estimates due to variation in the anatomical parameters were carried out and estimates of the uncertainty introduced by not having complete information on orientation and posture were calculated.

Two features of the organ-dose estimates that were introduced on the advice of the panel may contribute to future studies: capability to routinely calculate energy-fluence distributions within organs so that appropriate microdosimetric parameters can be estimated, and the ability to calculate the dose within various portions of single organs. An interesting example of the latter is the dose to bone marrow, an organ widely distributed throughout the body. From the example given in the report the gamma-ray dose varies by a factor of 2 or more, neutron dose by about a factor of 8 within the marrow. Such detailed information has important implications when nonlinear dose-response functions are fitted to leukemia mortality data.

o The organ dose models are up to date and were carefully applied. Thorough attention was given to testing the assumptions and characterizing the uncertainties in the organ-dose calculations by means of sensitivity analyses. The effects of _in utero_ radiation are of considerable scientific interest. At present the dosimetry system does not include organ-dose estimates for the fetus/embryo. The panel believes this deficiency should be removed as soon as practical.

9. The DS86 System

The final chapter in the binational report describes the DS86 dosimetry system now being used at RERF. DS86 is based on the results of the dose reassessment to date but is structured to allow the incorporation

of new information as it is developed, for example, shielding data for factory workers. The DS86 system avoids the use of integral quantities such as kerma, fluence, or shielding factors. Rather, information on the differential energy and angular fluence is assigned to each survivor, depending on his distance from ground zero, and then perturbed according to his individual shielding history, posture, orientation, etc. This means that if, for example, new shielding parameters are developed, only the block of information that uses the shielding data to change the differential fluence matrix need be replaced, while other parts of the dose estimation procedure continue as before.

The cost in computer time of handling all these data is considerable, approximately a half minute per survivor. It is not likely that much less computer time would be used by some other method such as classifying survivors by distance, shielding parameters, sex, age, orientation, etc. as the number of combinations would be quite large. Moreover, all survivors would become liable to reclassification upon system revision.

The DS86 system is designed to include not only organ-dose estimates but also estimates of the standard deviation of each organ dose calculated for an individual. Full utilization of this procedure must await completion of the formal uncertainty analysis as only limited information on the uncertainty of the dose estimates is incorporated now. Table 9.12 in the binational report[13] gives some preliminary estimates of the uncertainty in the various parts of the dose calculation but it does not always agree with the estimates of uncertainty given in the various chapters of the report, and certainly does not reflect the uncertainty in the neutron-dose estimates for Hiroshima that is indicated by the ^{60}Co data. The effects of the various sources of uncertainty are often highly correlated with each other; this should be examined carefully in the final uncertainty analysis of DS86.

The preliminary uncertainty analysis indicates that controllable uncertainties, due to sampling variation in the Monte Carlo studies and specification of detail in the modeling, have been held to about 5 percent. Other sources of uncertainty are more important. The uncertainty in a survivor's shielding due to the use of the available parametric data, his distance from ground zero, and his orientation may each contribute 10 to 20 percent standard error in the organ-dose estimates. However, in some circumstances, such as when orientation or shielding parameters are not available and average values must be used, the uncertainty due to a single factor may be 30 percent or more. Unfortunately, the total uncertainty cannot be estimated until the formal uncertainty-sensitivity analysis is completed.

o The DS86 dosimetry system is well conceived to fulfill the needs of the RERF. It is amenable to future development and should serve as the basis for any future amendments to the A-bomb survivor dosimetry that may be desirable.

IV. Conclusions and Recommendations

It is the panel's view that the binational working groups have done a very creditable job in carrying out the dose reassessment. DS86 provides a complete description of the dose to the organs of A-bomb survivors at given locations. Where information on a survivor's shielding and orientation is available, this can be used in a rigorous manner that takes full account of the directionality of the radiation. As compared with T65D, it incorporates new yield information, new source terms for both Hiroshima and Nagasaki, more sophisticated and tested transport codes, specific experimental verification of kerma in air by TL methods, and new calculations of shielding by structures and by organs. The results show that in Nagasaki the free-in-air kerma due to the gamma rays is slightly less in DS86 than in T65D. The kerma due to the neutrons is about half of that calculated under T65D. In Hiroshima, the FIA neutron kerma is reduced by about a factor of 10 while the gamma kerma is considerably increased under DS86 as compared with T65D. This increase is offset, however, by changes in the allowances for structural shielding and self-shielding under DS86 which tends to reduce gamma dose to internal organs. Eventually the DS86 will include a rather complete evaluation of uncertainties in the dose estimates.

The panel believes that the new dose estimates are more accurate and more soundly based than their T65D predecessors and that they should be used by RERF in its assessment of radiation effects. Notwithstanding this endorsement, the dose estimates provided by the DS86 system should not be used uncritically. They are estimates, not true doses, and are not error free.

As outlined above, many parts of the dose reassessment have redefined the state of the art in the dosimetry of nuclear weapons. The work on shielding and estimating organ doses from external radiation fields is germain to the solution of a number of problems in radiation protection dosimetry and will certainly be applied elsewhere.

The reassessment also illustrates the simple fact that retrospective dosimetry is very difficult. Historical records are never complete and experimental results have to be taken at face value without a thorough understanding of their limitations. The failure of the new dosimetry system to verify the slow-neutron activation of ^{60}Co at Hiroshima has been disappointing. Although work on this problem is expected to continue, little progress has been made in the past 24 months and the matter is unlikely to be resolved soon. The panel recommends that the disagreement between calculated and measured neutron fluences be included in the formal uncertainty analysis so that its importance can be quantified.

Ultimately the DS86 dosimetry system must provide a sound basis for the analysis of biological and epidemiological data. The panel recommends that biological effects data for persons in different shielding categories be compared to validate the dose estimates made under DS86 so that any discrepancies can be identified.

The full usefulness of the DS86 system cannot be realized until the uncertainty in the organ dose estimates have been properly codified and incorporated into the DS86 system. The preliminary estimates of uncertainty described in Chapter 9 of the binational report are indicative but inadequate. Quantitative information on uncertainty as a function of distance is an important parameter in the analysis of radiation effects but is not available as yet to investigators at RERF.

The panel understands that the uncertainty analysis could not be completed until the DS86 system was fully defined and documented. Nevertheless, the panel has been handicapped in its assessment of the DS86 system because uncertainties have not, as yet, been quantified. Any decisions on what portions, if any, of the DS86 system require refinement, can only be made in terms of their effect on reducing the uncertainty in the dose estimates. Such judgments cannot be made now and the panel recommends that the uncertainty analysis now under way at ORNL be thorough, be well documented, and be completed as soon as possible. Furthermore, the panel recommends that the DS86 be reviewed periodically so that it does not become obsolete. Moreover, any adjustments or additions to the system should be thoroughly documented and have appropriate technical review.

While it is too early to say what effect the new dose estimates will have on the interpretation of epidemiological studies being carried out at RERF and elsewhere, the new dosimetry does insure that future assessments of the A-bomb survivor data will be on a firmer scientific basis. It is not unlikely that additional dose estimates for A-bomb survivors will be put forward from time to time as new information becomes available. Even though such changes are not expected to be large, the new dosimetry system provides an ordered structure for their assessment and utilization by the scientific community. These are encouraging developments and the panel looks forward to continued progress in the dosimetry of the A-bomb survivors.

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APPENDIX I

EXECUTIVE SUMMARY*

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The Preface 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 appendices to the relevant chapters.

Chapter 1, Yield of the Explosions

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.

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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 tests Crossroads A and B. 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 at 676 m. 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 ratio 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 vs 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:

Hiroshima	15 kt
Nagasaki	21 kt,

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, Source Terms and Source Term Verification

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 and at Lawrence Livermore National Laboratory. 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 Los Alamos, a critical assembly using parts of a bomb of the type exploded at Hiroshima, but with a reduced amount of ^{235}U, was set up. 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^o (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 control the neutrons transported to distances 1 km or greater, there is a good basis underlying the calculated neutron doses.

A significant source of prompt gamma rays is the capture by the nitrogen in air of neutrons that were emitted from the bomb. 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, providing a verification of the calculations of prompt gamma rays from the Hiroshima weapon. Other weapon tests have provided good tests 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 0.9 km 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 mechanism of bomb explosion. The calculation is within the experimental error of the measurement.

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 the 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. 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) are 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 the Editor's Note) at various relevant distances up to about 2 km ground range is an essential step in determining 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 both 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 tranported 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 make a small correction to the air capture gamma rays but has not yet been calculated because the calculation is very difficult.

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 for ^{235}U, ^{238}U, and ^{239}Pu for fast neutron fission. Not all of these data are available. These sources must then be used in a time dependent geometry since the fission products circulate within the fireball, which itself is 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 in exploding bombs. 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. A complicating factor is that there are significant differences between different sets of measurements of the sources.

Fortunately, all these various transport calculations have been verified in a variety of separate experiments as well as by checking the results of calculations using different codes with one another.

Neutron transport was verified by comparison with the measurements of neutron fluences at distances up to 1 km in air from a bare reactor. Also, measurements of a pulsed neutron source in liquid nitrogen were compared with calculation. Finally, both fast and thermal neutrons were measured and compared with calculations at a number of weapons tests, for distances up to 2 km and greater. Except for thermal neutrons at distances less than 1 km, where there are still some discrepancies between calculation and measurement, there is good agreement between calculated and measured neutron fluences.

The situation with the gamma rays is more complicated because the number of delayed gamma rays is much larger than the number of prompt ones. The measurements at the bare reactor (APRD) served to verify the calculation of air capture gamma-ray transmission out to 1 km. 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 both similar yield and 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 give 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 order 2/3. The resulting calculations were combined with the prompt neutron calculations to attempt to fit thermal neutron activation data 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 1.2 km, but calculation appears to be consistently high by factors approaching 2 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 1 km. However, these deficiencies should not be important in the doses to the survivors.

Chapter 3, Section 7, summarizes the free-in-air kermas in tissue from neutrons and gamma rays from the new calculations, designated here as DS86, and compares them with the T65D system. At Nagasaki, the gamma-ray kerma for DS86 is larger than that for T65D by about 10 to 30%, depending on ground range; the DS86 neutron kerma is about 1/2 to 1/3 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; it 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 2 to 3.5, depending on ground range; the DS86 neutron kerma is about 1/10 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. The DS86 methods, the subject of this report, are calculations from primary physical data. The 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 that 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 one and two km in Hiroshima and Nagasaki should be in the 10% to 20% range assuming the initial sources to be correct.

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 from days with closely similar weather conditions were used to provide an atmospheric profile of density and humidity.

Chapter 4, Thermoluminescence Measurements of Gamma Rays

There are certain measurements of the radiations that provide direct measures of the gamma-ray and neutron doses at relevant distances. Thermoluminescent dosimetry (TLD) has been developed in the last 30 years; one of its goals was to evaluate the age of pottery specimens exposed to natural radiations. It has proved possible to use similar TLD techniques to evaluate the gamma-ray dose delivered to small quartz inclusions in 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 2 km, where the doses are about 0.2 Gy. Certain other techniques such as electron spin resonance measurements on shell buttons and teeth may also provide useful data in some instances.

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 (UH) in Hiroshima, Japan; the University of Utah (UH) in Salt Lake City, USA; Oxford University in Oxford, England; and Durham University (DU) 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 at various distances out to nearly 2,100 m in Nagasaki and in Hiroshima. Free-in-air kermas measured at Hiroshima range from 100 Gy near the hypocenter to about 0.35 Gy at 1,600 m. At Nagasaki, measured doses range from 200 Gy to about 1.2 Gy at 1,427 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 (NBS) and measured by the various laboratories.

Finally, the calculated gamma-ray spectra at various distances in Hiroshima and Nagasaki were used in a calculational procedure where the actual sample was modeled in its actual location in a building to give a calculated dose at depth 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 1,500 m, whereas they are within 25 or 30% out to 2,100 m in Hiroshima. Some other techniques have been used for after the fact dose determinations in Hiroshima and Nagasaki. Electron spin resonance (ESR) was used on a shell button of a doctor at a hospital in Nagasaki at 691 m range. 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, it can be difficult to compare these doses with calculations. But the technique could be invaluable in giving doses to actual survivors to compare with symptoms.

Chapter 5, Measurements of Neutrons

Shortly after the bombs 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 1 km. These data have been recently reevaluated to provide a reliable measure of the fast neutron fluence at close distances in Hiroshima. The activity induced in cobalt impurities in iron by the thermal neutrons was also measured as was the activity of ^{152}Eu induced in rock by thermal neutrons. 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 bombs, sulfur was extracted from electrical insulators in Hiroshima out to 1 km range. The ^{32}P activity was measured by a Lauristen electroscope. These data have recently been reexamined and reviewed and have been compared with calculations based on a yield of 15 kt and using 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 ($\approx$ 3 MeV) this means that 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 calculation gives a yield 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 1 km is dominated by source neutrons of energies greater than 1 MeV. Therefore the sulfur activation comparison is important in bounding 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 buildingsand in other uses in buildings. The activation of cobalt is due to thermal neutrons; at some depth in concrete the effects of incident epithermal neutrons predominate. 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 a calibration using an inappropriate (bare reactor) source to convert the data to kerma. Loewe found that the calculated activity ranged from 1.5 times that measured at 290 m to 0.3 times at 1,180 m.

In attempting 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 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 1 km. 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 Dose from Residual Radioactivity

Fallout of fission product activities contributed additional irradiation to certain individuals in a few locations where there was a significant fallout. The fallout was measured some weeks or months later and the initial activity could be inferred approximately providing stormshad 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 1 km of 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 of 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 1 hour (about the time of the fallout) to infinity can be calculated after fitting to measurements made one or more months after the bomb. The absorbed dose from gamma rays for persons continuously in the fallout area from 1 hour to ∞ ranged from about 0.12 to 0.24 Gy at Nagasaki. The absorbed doses at Hiroshima ranged from 0.006 to about 0.02 Gy. 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 1,000 hectares. Estimates of the internal dose from ingested ^{137}Cs are based on whole body measures of 10 to 13 pCi/kg, yielding about 0.0001 Gy integrated over 40 yr.

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; ^{46}Sc - 1 R; giving a potential total absorbed dose of about 0.5 Gy at Hiroshima and about 0.18 to 0.24 Gy at Nagasaki. These doses would be reduced to two-thirds if the person arrived at the hypocenter 24 hours after the bomb and to 1 or 2% after a week. The exposure, of course, falls off at greater distances.

The critical factor in making use of the above estimates of potential 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 doses to about 2/3.

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 unexposed 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. This shielding gave a reduction in the dose compared with that a person in the open would have received so that it is necessary to include some estimate of shielding in evaluating the actual dose. The procedure used to evaluate the shielding of a typical house or house cluster was to:

1. Construct a computer model of a house or house cluster using the best information available about the dimensions, materials, and thicknesses 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 n-γ 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 non-uniform 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 principle 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 1,500 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 is the so-called "nine parameters". Twenty-one points in the six house cluster and forty 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 well correlated 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, US.

The shielding system then selects all computed cases for a given parameter set and averages the leakage tapes for those cases to give asingle 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, "the neutron free field-weighted, unblocked fraction of the solid angle," or WUBF, correlates best with the transmission. 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 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, $\leq$ 3 yr, a 9.7 kg phantom was used whereas for ages between 3 and 12 yr 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 45o to the trunk.

The calculational method is the same as was 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 Appendices 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 is approximately equal to the kerma (see Editor's Note); in DS86, they are equated. The exception is the bone marrow; charged-particle equilibrium does not exist and special calculations of the dose were made (Appendix B-8).

The organ dose system applied to phantoms has been compared with experiment with very good agreement for isotropically incident gamma rays. 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 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 (DS86)

This chapter describes the computerized system, called 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.

The 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.

APPENDIX II

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