DOE Symposium Series 55

Reevaluations of Dosimetric Factors Hiroshima and Nagasaki

Technical Information Center, U.S. Department of Energy

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Hiroshima and Nagasaki

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Foreword

On behalf of the Department of Energy, and especially of the Office of Health and Environmental Research, I welcome you to this workshop, which has for discussion such an enormously important subject matter. John Auxier in his book *Ichiban* explains that the program of determining and supplying individual doses to the population under study by the (then) Atomic Bomb Casualty Commission was termed the Ichiban project because of its importance to the study (the Japanese word "ichiban" means "the most important," "the best"). That was in the late fifties, and, as we all know, the output of the Ichiban project was the set of tentative doses known as T65D. Since then, slowly at first, but at an accelerated pace especially during the last few years, data have become available and analyses have been performed which indicate considerable discrepancies with T65D. We find ourselves now at the point when a complete review of all relevant data has become necessary, in order for us to proceed in an expeditious manner with the task at hand, which is the comprehensive reassessment of exposures and absorbed doses for some 100,000 people under study and follow-up by what now is called the Radiation Effects Research Foundation (RERF) of Hiroshima and Nagasaki. A rather extraordinary coincidence, I thought, occurred when, at the first more-extensive discussion of this subject, this summer at a meeting of the Radiation Research Society in Minneapolis, Minn., participants noticed a Japanese restaurant across the street named Ichiban! Whether this is an omen or not, it is true that the goals of Ichiban are still alive and that what we intend to do here is still within its bounds.

The Department of Energy (DOE) is committed to the support and coordination of research efforts necessary for the complete and expeditious revision of T65D. This workshop is one of the means of assisting the Department in discharging its responsibility. We have also requested that the National Academy of Sciences–National Research Council establish a committee "to ensure that decisions in this effort are made on a firm and credible scientific basis" and "to ensure that the results will adequately support the RERF programs." The main objectives of this workshop are (1) the determination of the current status of research efforts and (2) the assessment of directions and levels of research efforts in the immediate future. We would also very much like to obtain a general plan for the total effort, with—as well as that can be done at the present time—major milestones and an estimate of the end point in time. I hope I have made it clear that we expect this workshop to be not just a process of information exchange in a contemplative sense but, above all, an action-oriented discussion that will help us, as research administrators, to facilitate getting the necessary efforts under way.

Unquestionably there is widespread and deep interest in the subject at hand. Our Japanese counterparts in RERF and in the government have already established an official Review Committee and a Scientific Study Group for the dosimetry reassessment program, and we expect a vivid discussion of the subject at the upcoming Science Council meeting of RERF in Hiroshima on September 28 and 29. Both Mr. Jablon and I will attend that meeting and report on the proceedings of this workshop. In this context I would like to acknowledge two representatives of the Japanese Government and scientific community present here today: Mr. Mizuta, Health Attaché at the Japanese Embassy in Washington, D. C., and Dr. Maruyama of the National Institute of Radiological Sciences, in Chiba, Japan, a member of the Japanese study group that I just mentioned.

It is our intention to facilitate a smooth flow of information between the investigators, DOE, the National Academy of Sciences committee, and the Radiation Effects Research Foundation and, from all of these, to the scientific community at large.

We are fully aware of the great interest in these studies of national and international advisory groups concerned with the effects of ionizing radiation on human populations or charged with the development of standards for protection against such radiation. Although this workshop will address some of the issues connected with the use of dosimetric data for risk assessment purposes, we do not consider this to be one of its primary objectives. At this stage our major concern is the dosimetric support of the studies carried out at RERF. Of course, we will coordinate all our efforts with groups that use the same data base, such as the National Council for Radiation Protection and Measurements and its Task Group on Atomic Bomb Survivor Dosimetry. But, as I said before, our major interest now is the dosimetry study itself. We feel that any really valid conclusions as to the biological implications of the incomplete data available at this time are, necessarily, of a tentative if not speculative nature.

I wish to thank Dr. Bond and his staff at Brookhaven National Laboratory for their splendid efforts in putting this workshop together under extreme pressures of time. Above all, I would like to thank the speakers at this meeting because it is upon them we all rely for the completion of the task at hand. We expect all of you here to participate in the discussions and to make any recommendations or comments that you consider worthwhile making. I can assure you that they will not fall on deaf ears.

J. W. Thiessen
Conference Coordinator

Preface

May I add my own word of welcome to this symposium on the reevaluation of dosimetric factors for Hiroshima and Nagasaki. The objectives of this symposium, or workshop, "Reevaluation of Dosimetric Factors, Hiroshima and Nagasaki," are rather narrowly focused. They are to evaluate past, ongoing, and projected work on the series of factors involved in the dosimetry for the exposures at Hiroshima and Nagasaki. The central assumption or thesis is that, obviously, studies and thoughts on dosimetry are in a state of reevaluation and flux. Otherwise we would not be holding this symposium. More specifically, no individual or group appears as yet to have carried more recent calculations completely through all shielding to obtain organ dose, from which exposed individuals can be regrouped to examine organ dose–incidence relationships. Such final calculations may well redistribute appreciably current (T65) individual assignments to dose groups. Thus, until such possible redistributions are determined, any dose–incidence relationship reevaluations must be viewed as tentative.

With this uncertainty in the dosimetry, it is not particularly productive to dwell at length, at least now, on radioepidemiologic factors and results. Such results must of course be evaluated when there is general agreement on the dosimetric parameters, with estimates of the confidence limits, to be made at some point in the future. We hope this will be soon.

Thus, although radiobiology is clearly not excluded from this symposium—it plays a prominent role, as a matter of fact—and although certainly the aim is not to deny or limit discussion, in our view the biologically oriented discussion should be limited essentially to generic relationships between the physics and the biology.

For those people working directly with the dosimetric factors, this is a workshop. A number are present, however, who work closely with the radiobiological or radioepidemiological data from Hiroshima and Nagasaki but who are not involved in dose calculations. These people are here for information, to learn exactly where we stand on the dosimetric evaluations. For them this is principally a symposium.

This is obviously an open symposium, and this may present a problem with respect to classified material, particularly in some subject areas. Clearly, classified material must not be discussed here. The entire symposium proceedings are being taped. Except for the presentations of the principal speakers, who will furnish manuscripts, the proceedings will be transcribed, including all questions, answers, and discussions. The discussions will be edited and sent to the appropriate individuals for modifications, as they may deem necessary. There will be limited discussions associated with each presentation. However, there are several periods for general discussion when any unfinished presentations or discussions can be reintroduced. Also, a long period is allotted for discussion at the end of the symposium, so that any remaining problems or questions can be aired and talked out.

The Technical Information Center of the Department of Energy (DOE) at Oak Ridge, Tennessee, is the publisher for the proceedings. The editorial personnel for the proceedings are Mary Hill and Jean Smith of the DOE Technical Information Center and Margaret Dienes of Brookhaven National Laboratory. The indexer for the publication is Axel C. Ringe, Science and Technology Division, Technical Information Center.

Finally, as you know, the symposium was organized in a very short time, and a great deal of effort was required by both the organizers and the speakers. In this regard, I wish to thank my assistant, Janice Lamb, for the extensive effort and overtime she devoted to the organizational matters. Also, Susan Rose and her associates at the DOE Headquarters in Germantown deserve a great deal of credit in this regard. I especially wish to thank all the speakers, who displayed much more cooperation and patience certainly than I think I would have under the circumstances in preparing abstracts and manuscripts in the short period required.

V. P. Bond
Conference Chairman

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Early Atomic Bomb Casualty Commission Perceptions and Planning

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School of Medicine, Case Western Reserve University, Cleveland, Ohio

The place to begin is at the beginning, but I have something to say before the beginning. This concerns the kind of research that was carried on by the Manhattan Project. The name of the Manhattan Project is unusual because it is derived from the Manhattan Engineer District, which was part of the Corps of Engineers. The name Manhattan was unusual for an engineer district because the districts were identified in those days by region: Southwest, Northeast, and so on. Therefore the name conveyed to the cognoscenti that this engineer district was out of the ordinary. Eventually, the Manhattan Project covered all the activities carried on under the Manhattan Engineer District auspices. The original work, incidentally, was begun under the Office of Scientific Research and Development. I believe Vannevar Bush was the chairman.

The research that the Manhattan Project carried on during World War II had to do with a better understanding of whether the scientists had correctly identified acceptable radiation levels and whether any immediate research was needed to support such levels. Before long, this burgeoned into studying more biological effects than were perhaps necessary for that immediate particular goal. Although attempts were made to confine the work to what was needed for the war effort, studies, nevertheless, were going on which were indirectly related to long-term effects. In looking through the records lately for various reasons, I found that in 1945 many reports were beginning to appear under the auspices of the Manhattan District or the Corps of Engineers. These were studies on tumor production in animals and some studies of nonspecific life-shortening.

Scientists at the National Institutes of Health, sponsored by the Manhattan Project through the University of Chicago, were carrying on long-range long-term projects in which animals (primarily mice) were irradiated with 0.1 rad/day, up to several rads per day, simply to observe what changes they could find. This went on for several years; so they had a chance to observe some late changes, and they actually did identify leukemia levels that were higher than the spontaneous levels.

In Rochester in 1945 there was a fairly long dissertation by Drs. Curt Stern and Don Charles, both geneticists, who were working on *Drosophila* for the mutations due to radiation. They included dire warnings in their reports that there ought to be careful examination of the long-term effects, particularly mutations. Many of the people in biology and medicine referred to the people who were studying *Drosophila* as Drosophilosophers and were not much moved by the kind of information that was available. But it is necessary to know that this occurred as a Manhattan Project activity.

When the nuclear strikes occurred in Hiroshima and Nagasaki, an early examination of the immediate effects was called for. I was then, at the end of the war, deputy chief of the Medical Division of the Manhattan Corps of Engineers, and the late Dr. Stafford L. Warren was the chief. We were not aware that we might be involved in such an assessment, because there was some question as to whether the Manhattan Engineer District would be modified or disbanded or whether the whole project would be taken over by the Army proper or shifted to civilian groups. We were suddenly informed that we would have to go to Japan in a great hurry. I was rushed from Oak Ridge to Washington, D. C., where I spent the night in Gen. Leslie Groves's office on a cot. During this hectic 24-hour period, I was instructed to assemble a group who knew how to make dosimetric measurements and who knew something about the biological effects of radiation as well. It was intended that they go to Japan promptly. Originally it was planned that I would remain and that only Stafford Warren would go, but things happen quickly in the Army, and before I knew it I too was on my way to Japan. We were rushed to Hamilton Field near San Francisco and were quickly on our way. We did not get to Japan immediately, for reasons I will not go into. Our center of operations was in Tinian, where the strike planes had taken off. From there we finally got into Japan—to Tokyo and eventually to Hiroshima and Nagasaki.

We spent about 10 days making studies in Hiroshima and Nagasaki. There was great devastation in both cities. Some slides I have showing this were originally classified but have long since been declassified and are in various reports. We went into these areas and made appropriate dosimetric studies. We had the necessary equipment—various dosimeters—for making the measurements, and we brought back an isodose drawing of the whole of Hiroshima with the residual levels. We also recorded such immediate biological effects as we could observe. These were, in part, relayed to us by several medical officers of the Japanese Army. It was very difficult for us to communicate because we did not understand Japanese and they did not understand English very well. We had a smattering of German between us so that we were able to identify a fair amount of information on a number of casualties that they had observed. We brought back records of the findings that had been accumulated.

The data, on huge rolls of paper, were brought back and transferred somewhere into the bowels of the Manhattan Project. Frankly, I have never seen them since then. I do not know where they are. I do not know that anybody knows where they are, but somewhere this information resides. When we got back from Hiroshima to Tokyo, we were asked to brief Cols. Averill Liebow and Ashley Oughterson, both of the Army Medical Corps. We gave them a fair amount of background on what we believed were the biological effects, and we told them what we had observed. Our surveillance had two primary objectives: (1) to measure the residual radioactivity and assess any immediate hazard to occupying forces and (2) to consider the feasibility of long-term studies. The major problem was to provide information for the occupying forces as to whether there were any immediate radiation hazards. Frankly, there were essentially none at that time. But one must remember that we became involved rather late.

One of the people there with us was a physicist well known to many of you—Dr. William Penney, now Lord Penney, from England. He came to measure blast damage. Another one was Dr. Robert Serber, who was taking samples of soil to see what kind of induced radioactivity had occurred.

We made a considerable number of dosimetric studies, and we prided ourselves on having done them carefully. We were able to discover some radium that the Japanese had lost, which we sealed up and eventually returned to them. We considered that a mark of the excellence of our work.

When we returned stateside in November, the question immediately arose as to what should be done about continuing surveillance for long-term effects. We were already aware that long-term effects could be important. One of the major aspects concerned the effects occurring within one year or so of the injuries. We also knew that clearly there would have to be very good information on dosimetry if this was to be utilized for projecting what kind of remote biological effects would occur. To that end there was considerable discussion in various circles as to how we should proceed. Because the Manhattan Engineer District was a temporary organization, it was not certain that this organizational unit or even the Army proper would carry out the long-term studies. It was also not certain whether any ensuing American organization would take this responsibility, because there was some question as to how long Japan would be occupied and in what manner.

In pursuance of this, a letter was written, sometime before June 24, 1946, by Surgeon General of the Army Norman T. Kirk to Lewis Weed, chairman of the Division of Medical Science of the National Academy of Sciences, asking the Academy to set up a program or to set up a group that would make recommendations in this regard. (Things have not changed much since then: difficult problems are turned over to some agency with the question, "What do we do now ?") On June 24, 1946, a committee on atomic casualties was formed by the National Research Council and the National Academy of Sciences. There were some 20 of us. The chairman was Dr. Cornelius P. Rhoads of Memorial Hospital for Cancer and Allied Diseases, in New York City. The members (with their then affiliations) were as follows:

Chairman

C. P. Rhoads

Members

S. D. Aberle, National Research Council, Washington, D. C.
H. L. Barnett, 525 E. 68th Street, New York City
Gilbert W. Beebe, National Research Council, Washington, D. C.
Gordon T. Bowlos, State Department
Detlev W. Bronk, University of Pennsylvania, Pittsburgh, Pa.
Michael E. DeBakey, National Research Council, Washington, D. C.
Louis I. Dublin, Metropolitan Life Insurance Co., New York City
R. E. Dyer, National Institutes of Health, Bethesda, Md.
Hymer L. Friedell, Case Western Reserve University, Cleveland
Edward C. Hammond (Major), Office of the Air Surgeon
Robert Hotchkiss, 65 E. 66th Street, New York City
Milton L. Kramer, 136 Waverly Place, New York City
George LeRoy, Army Institute of Pathology, Washington, D. C.
Averill Liebow (Lt. Col.), Army Institute of Pathology, Washington, D. C.
James C. Magee, National Research Council, Washington, D. C.
Ashley W. Oughterson, American Cancer Society, New York City
Philip S. Owen, National Research Council, Washington, D. C.
Roger G. Prentiss (Col.), Office of the Surgeon General, War Department
Jack D. Rosenbaum, 256 Park Street, New Haven, Conn.
W. H. Sobrell, National Institutes of Health, Bethesda, Md.
Robert S. Stone, University of California Hospital, San Francisco
A. P. Webster (Comdr.), Bureau of Medicine & Surgery, U. S. Navy
Lewis H. Weed, National Research Council, Washington, D. C.
T. L. Willmon (Capt.), Bureau of Medicine & Surgery, U. S. Navy
M. M. Wintrobe, Salt Lake General Hospital, Salt Lake City, Utah

The committee made the following recommendations:

1. One or more members should be sent back to Japan immediately to make some assessment of whether indeed the work could be carried out; the Japanese should be encouraged to participate actively, which is an interesting aspect.

2. A long-term commission should be set up to do the studies. The committee recognized the difficulties that might be encountered. There were yea-sayers and naysayers (like everywhere else), but they eventually recommended that the commission be set up either under the Army, with an advisory committee from the National Research Council, or independently, as a special commission.

The committee believed that setting up a special civilian commission would be very difficult; nevertheless that is what was eventually done, with concurrence of the Army. The letter containing the recommendations, sent by Dr. Weed, went back to Gen. Kirk with suggestions for implementation which, in turn, had to be reviewed by the Manhattan District. I actually have a copy of this second letter, written by the Surgeon General's Office, in which there was endorsement by Gen. Groves. One of the reasons for this somewhat tortuous process was the fact that the Medical Corps and the Manhattan District were both under the command of Gen. Styer, who was chief of the Service of Supply. Thus the eventual Atomic Bomb Casualty Commission was initiated and came into being.

The explicit formation of a structured atomic bomb casualty commission was promptly pursued by the Atomic Energy Commission under the urging and guidance of Dr. Shields Warren, who was the director of the Division of Biology and Medicine.

Development of the Dosimetric Program, T65D Values

JOHN A. AUXIER
Oak Ridge National Laboratory, Oak Ridge, Tennessee

ABSTRACT

In 1956 the Health Physics Division of Oak Ridge National Laboratory undertook the task of developing a method of evaluating the radiation doses received by the survivors of the nuclear bombings of Hiroshima and Nagasaki, Japan. Data for this project were obtained from nuclear weapons tests, Operation BREN, laboratory experiments, physical surveys in Japan, and calculational studies. The approach to the problem was as fundamental as possible, with emphasis on quantitative measurements and calculations of the energy, angular, and spatial distributions of weapons radiations in an air-over-ground geometry. Spatial distributions of dose in various shields, including Japanese dwellings, were measured. Techniques were developed in Japan for verifying the locations of survivors and accurately describing their shielding environments. Simple empirical equations were developed which permitted the calculation of the shielding factors for Japanese residential-type structures.

It was not until Operation Teapot at the Nevada Test Site (NTS) in 1955 that the Health Physics Division of Oak Ridge National Laboratory (ORNL), in collaboration with Los Alamos Scientific Laboratory, completed a series of experiments which provided important new understanding of weapons radiation fields. Tetrachloroethylene chemical dosimeters (Sigoloff, 1956) were used to measure gamma-ray doses, and the neutron fluence distributions were measured with threshold detectors (Hurst et al., 1956; Reinhardt and Davis, 1958). Dose–distance relationships, D(R), for both fast-neutron and gamma radiation were shown (Glasstone, 1962; Harris et al., 1955) to be

$$D(R) = \frac{G_0 e^{(-R/L)}}{R^2}$$

at distances greater than about one relaxation length, where G_0 is a function of the yield and design of the weapon, and L is the relaxation length for the type of radiation considered. For a particular detonation,

$$L = \frac{\rho_0}{\rho} L_0$$

where ρ is the air density and ρ_0 and L_0 are the values for these factors at an air density of 1.29 g/liter. Dose, as used here, is the tissue kerma in air above the air ground interface. The distance, R, is "slant distance" or distance from the explosion to the point of measurement rather than distance from ground zero, the hypocenter. Gamma-radiation exposure and neutron dose and fluence as a function of distance are shown for a typical detonation in Figs. 1 and 2, respectively. Also, it was shown, for distances greater than $R/L \simeq 1$, that the neutron energy spectrum was, to a close approximation, constant, i.e., an equilibrium spectrum was obtained (Fig. 2). These data have been discussed in detail by Ritchie and Hurst (1959).

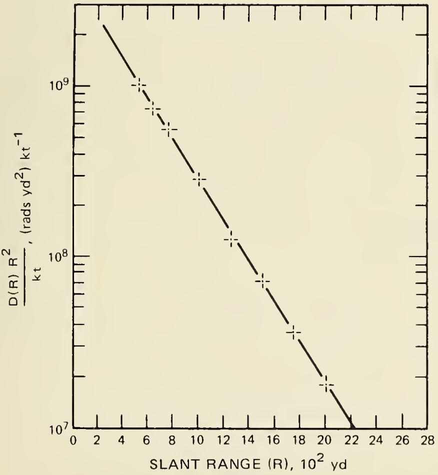


Fig. 1 Gamma dose as a function of slant range for a typical nuclear detonation.

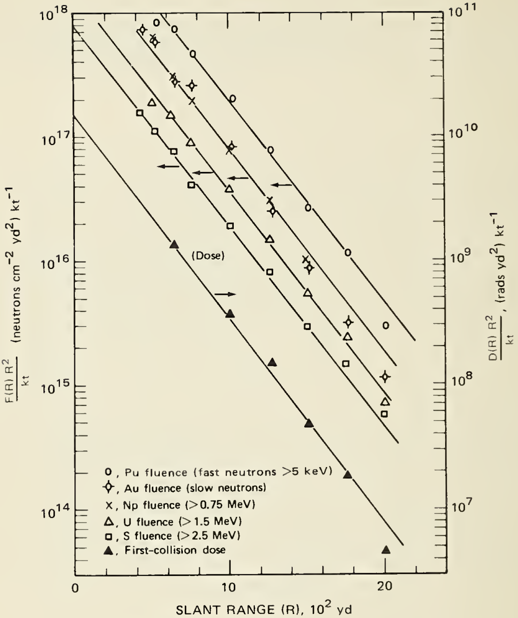


Fig. 2 Neutron dose and fluence as a function of slant range for a typical nuclear detonation.

The data from Operation Teapot indicated the possibility of a definitive description of the radiation fields from the Hiroshima and Nagasaki bombs. Consequently, early in 1956 a survey team, including members from Los Alamos Scientific Laboratory, the Medical College of Virginia, the U. S. Atomic Energy Commission (Division of Biology and Medicine), and Oak Ridge National Laboratory, visited the Atomic Bomb Casualty Commission (ABCC) in Hiroshima and in Nagasaki with the objective of determining the feasibility of a dosimetry study. After reviewing records and examining typical shielding configurations, the survey group recommended that a dosimetry program be initiated. Emphasis was to be placed on persons exposed in Japanese dwelling-type buildings because of the high structural uniformity and the large fraction of survivors exposed in such buildings.

As a result of the recommendations of the survey group, a program designated Ichiban was established in the Health Physics Division of Oak Ridge National Laboratory.

The overall problem was divided into three parts: (1) documentation of the location of the survivor at the instant the bomb exploded; (2) establishment of the dose–distance curves; and (3) determination of the shielding factors for the houses. After work with the ABCC, the solution of the first part of the problem was reduced to a matter of time and required little research. The second part was further subdivided into two segments: (1) determination of the shapes of the curves during weapons tests and (2) normalization of these curves to the radiation yield of the subject weapons. From the beginning of this investigation, the problem of normalization was expected to be the most difficult.

OPERATION PLUMBBOB

A pilot study of neutron and gamma radiation dose distributions in Japanese houses was conducted during Operation Plumbbob at NTS in 1957. A larger and more fundamental study of the dose distributions in air for several weapons was also carried out during this operation (Hurst et al., 1958). Two replicas of a typical Japanese residence were constructed at NTS (Fig. 3). In addition, 120 collimation devices were constructed to permit measurement of an angular distribution of the radiation field incident on a point detector in an open field (Fig. 4).

Data from Plumbbob indicated that the radiation fields in Japanese houses might be related, in general, to a few identifiable parameters such as house size, orientation, mutual shielding, and proximity of walls and windows. The basic program provided a description of the angular distribution of radiation (Fig. 5), especially for fast neutrons, and shielding information on building materials. The greatest uncertainties in the dose–distance distributions involved the gamma radiation.

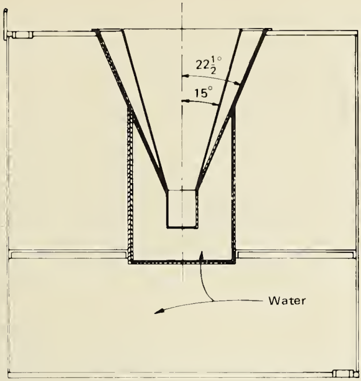
Upon completion of the analysis of data from Plumbbob, a summary of all dosimetry information applicable to the survivors was prepared and transmitted to the shielding group of the ABCC. Designated T57D, this tentative dosimetry information served as a guide to the establishment of techniques for determining dose values from the shielding "histories" of the exposed individuals; also, it provided an estimate of dose which supplanted the use of distance as the correlative factor for observed responses. These dose–distance curves were provided by York (1957) and were based on all weapons data available to him in 1957. The uncertainties in the curves were large, and the doses obtained from them were assumed to be no better than within a factor of 2.

Fig. 3 One of two Japanese houses used for dosimetry studies during Operation Plumbbob.

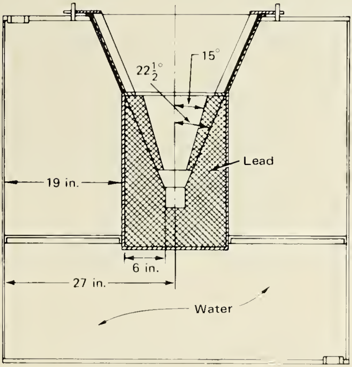
After Operation Plumbbob, laboratory studies of the shielding coefficients of Japanese and domestic building materials were conducted. Cement–asbestos board, commercially available in large sheets, was found to be suitable as a substitute for the wall-plaster mixture of clay, oyster shells, and seaweed and for the mud-tile roofs of Japanese houses for experiments with both neutrons and gamma rays. The spacing of the wood framing used in Japan fitted well with the substitution of cement–asbestos board. Consequently, it was planned to use radiation analogs of Japanese houses for any further field experiments.

OPERATION HARDTACK II

Late in 1958 a weapons test series, Operation Hardtack II, was conducted at NTS, and further work was directed to the measurement of radiation fields inside Japanese houses (radiation analogs constructed of cement asbestos board in wood framing typically used in Japan). Emphasis was placed on the determination of the radiation fields as a function of house size, orientation, and position relative to its neighbor.

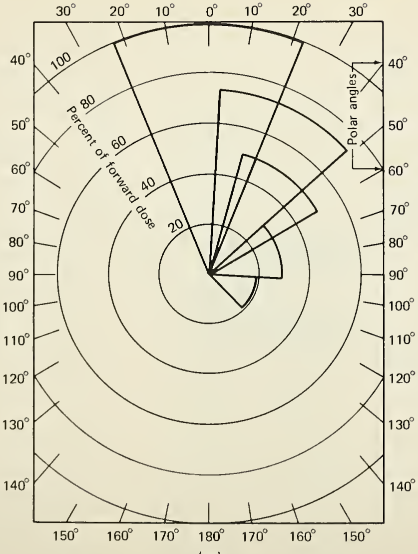


NEUTRON COLLIMATOR

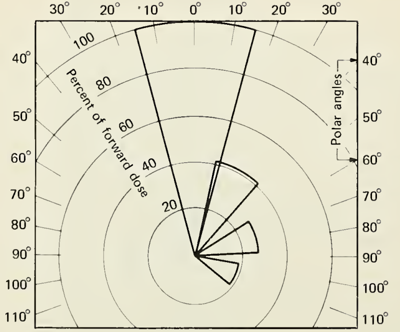


GAMMA COLLIMATOR

Fig. 4 Collimator devices used for measuring the angular distribution of radiation from nuclear weapons.



(a)



(b)

Fig. 5 (a) Relative neutron dose intensity and (b) relative gamma-ray dose intensity coming into a point from a solid angle defined by the angle of collimation of radiation. Triangular areas show the collimator aperture and angle relative to the direction to the detonation, with the intensity at zero angle normalized to unity.

Seven houses were constructed and, because of the durability of the wallboard and other fortuitous events, six were repaired and used three times; the seventh was used twice. One array of houses is shown in Fig. 6.

With all the data available after Hardtack II (Auxier, Cheka, and Sanders, 1961), it was possible to compute the neutron dose at any point in a Japanese house for a large number of typical configurations. The neutron data were generally satisfactory; some refinements in the angular distribution at small angles were needed, but the neutron program was in an advanced stage. There were, however, apparent discrepancies in the gamma radiation data compared with earlier data. At the time, these discrepancies were attributed to the inadvertent substitution of lithium depleted in ^{6}Li in the thermal neutron shields used with the chemical dosimeters.

OPERATION BREN

Consequently, it was decided to do a definitive study of the neutron and gamma radiation fields at large distances from a point fission source.

Fig. 6 Typical array of Japanese houses (radiation analogs) used during Operation Hardtack II.

The ORNL Health Physics Research Reactor (HPRR) (Fig. 7) was suspended on a hoist car that was mounted on a 1527-ft-high tower at NTS (Fig. 8). Designated Operation BREN, the experiments were conducted during the spring and early summer of 1962 (Auxier et al., 1962; Sanders et al., 1962). Major objectives of Operation BREN included the energy, angular, and spatial distributions of neutrons and gamma radiation from the HPRR; also a ^{60}Co source of a nominal 1200 curies was substituted for the reactor upon completion of the reactor studies. Measurements of spatial distributions of dose were extended to radiation analogs of Japanese houses. The radiation fields inside Japanese houses were deter-

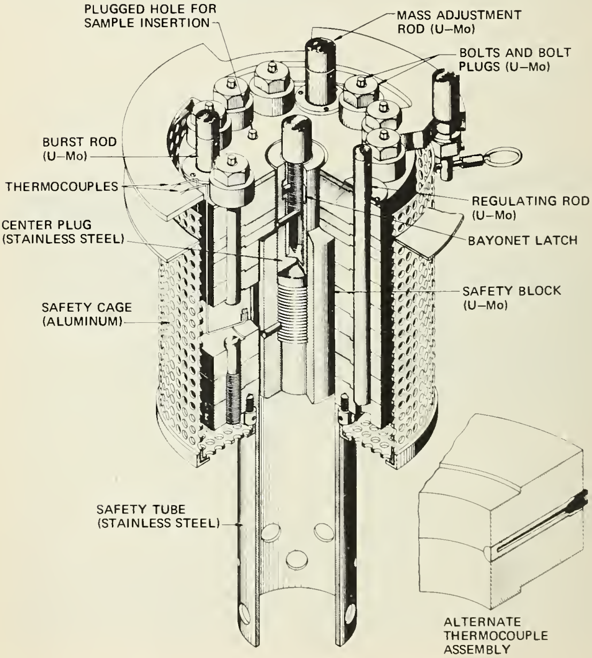


Fig. 7 The Health Physics Research Reactor.

Fig. 8 The Health Physics Research Reactor mounted on hoist car on the BREN tower.

mined as a function of house size, orientation, and position relative to other houses. All measurements were made with sensitive laboratory-type instrumentation, and only the spectral measurements for gamma rays from the fission source were considered to be marginal; with maximum reactor power (for continuous operation) and the most sensitive instruments, it appeared unlikely that the desired accuracy could be attained. Although considerable information concerning the spectrum was obtained, the number and distance range of these measurements were limited. However, all other phases were highly successful. Gamma radiation fields in the houses were found to be similar to those during Operation Hardtack II, and they were consistent and reproducible. A small Japanese "house" and a cement–asbestos "house" of identical size were found to yield identical data. These data, with those from later laboratory experiments, confirmed the hypothesis that neutron interactions with the major elements of the houses and buildup due to scattering of the high-energy gamma rays (from neutron interactions in the air) resulted in the observed gamma distributions; the net "attenuation" of gamma radiation was found to be small, and frequently there was a net increase in gamma radiation dose at points inside the house.

In addition to improved shielding information for houses, significant contributions were made to the description and understanding of the radiation fields at large distances from nuclear weapons and other intense radiation sources. Of special significance are the data on the effect of the air–ground interface (Auxier, Haywood, and Gilley, 1963; Haywood, 1965).

By early 1964, final equations were developed for obtaining shielding factors for Japanese houses which technicians can use for computing shielding factors. For neutrons, the expression

$$\frac{\text{Shielded dose}}{\text{Air dose}} = A_1e^{-G_1} + A_2G_2 + A_3G_3 + A_4G_4 + A_5G_5 + A_6e^{-G_6} + A_8G_8 + A_9$$

yields shielding factors accurate to within ±50% confidence level. The constants A_i have all been determined by multiple linear-regression analysis, and the geometry factors G_i are physical dimensions taken from the shielding "history" of interest. The geometry factors G_i describe the penetration distance of the direct radiation through the house, the number of interior walls shielding the survivor from the front, the number of interior walls shielding the survivor from the side, the lateral shielding exterior to the house of the survivor, the frontal shielding exterior to the house of the survivor, the height above the air–ground interface, and the distance from an open window in the direction of the hypocenter. For gamma radiation

$$\frac{\text{Shielded dose}}{\text{Air dose}} = A_1A_2e^{-G_1} + A_2e^{-G_1} + A_4G_3 + A_5G_4 + A_6G_5 + A_7G_6$$

is used; the 50% confidence limits are less than ±6%. The constants A_i and the geometrical factors G_i are different for each of the two equations and for each city. Confidence limits are based on a comparison of approximately 600 datum points from weapons tests and Operation BREN.

The remaining aspect of the problem was the normalization of the dose–distance distributions to the radiation "yield" of the Hiroshima and Nagasaki bombs. An analysis of early postbombing studies of neutron activation yielded no useful information; apparently samples were collected without sufficient regard for their precise location at the time of detonation. Later studies of steel samples were little better. In early 1963 a group at the Japanese National Institute of Radiological Sciences headed by T. Hashizume (Hashizume and Maruyama, 1975) commenced an activation study in collaboration with the Ichiban dosimetry group. In these studies, only samples of steel which were several centimeters deep in concrete at the tops of buildings and which had not been disturbed were analyzed. The HPRR was used in calibration studies. Similar studies were concerned with the radiation-induced thermoluminescence in Japanese roof tiles (Higashimura, Ichikawa, and Sidei, 1963).

Ideally, the method of normalization of the air-dose curves would have been to refire exact duplicates of the weapons used in Japan, at a suitable test site. However, testing in the atmosphere was prohibited, and other methods were used. These included radiation "leakage" studies of duplicates of the original bombs, extensive calculations, and extensive comparisons of all physical and biological effects of the two weapons with each other and with all available data from weapons tests. The understanding gained during Operation BREN of the air–ground interface and height-of-burst effects on the radiation fields was of utmost importance. Accounting properly for these effects removed apparent anomalies in comparing the Nagasaki effects with those from similar bombs used in tests and, in turn, clarified problems in comparing the Hiroshima and Nagasaki effects. Furthermore, the extensive "nuclear archaeology" studies conducted in various U. S. military archives, with various members of the air crews who participated in the bombings, and with the early weapons scientists, indicated that the yields of the bombs were 22 and 12.5 kt equivalent of TNT for Nagasaki and Hiroshima, respectively. The value for Nagasaki was clearly 22 ± 2 kt, but the data for the Hiroshima bomb were less certain. Verification of the ORNL values by an independent study of his old data by W. G. Penney of Great Britain (1970) gave assurance that the yield was between 11.5 and 13.7 kt; 12.5 ± 1 kt, for one standard deviation, appears well justified. Lord Penney's recalculation was based on photographs and distance measurements supplied by the ABCC and ORNL. Dose–distance curves (Fig. 9), normalized to the newly determined kiloton yields and designated T65D to show that they were still tentative, were provided to the ABCC in 1965 (Auxier et al., 1966).

EPILOGUE

Scientific work either must withstand the hard scrutiny of further work and time or it must be replaced. When lack of funding brought the Ichiban studies to an end, the data, the analyses, and the assumptions were the best possible. The greatest uncertainty in the T65D curves was taken to be the neutron spectrum for Hiroshima (Auxier, 1977). There have been no significant contributions to the study over the intervening years, and we still await a multidimensional hydrodynamic calculation of the spectrum. In the interim it is clear that further work will either substantiate or modify the T65D values, and, until all evaluations are completed, it would appear premature to change our existing perceptions of the dose–response relationships based on the T65D values.

ACKNOWLEDGMENT

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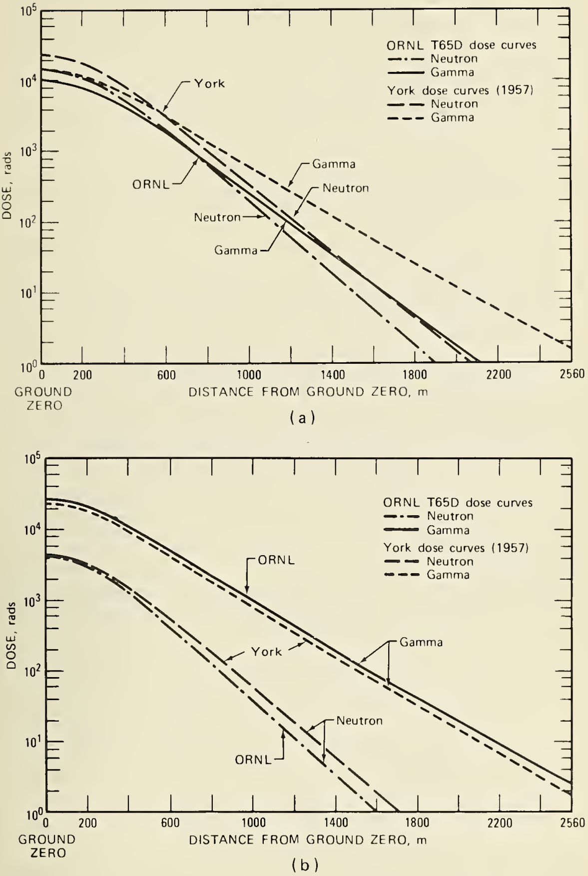

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DISCUSSION

Sinclair: What was the basis for the plot of the weapon's neutron-leakage spectrum? Was it based on a calculation of the spectra or on the californium measurement in the mockup?

Auxier: The first value ever used (0.76) was based on the measurement of the spherical assembly at Los Alamos, which happened to agree closely with the calculations. Two groups at Los Alamos did calculations. I cannot describe the state of the art either then or now, but one group calculated a value of 0.56 neutron per fission and the other a value of 0.81 or 0.83. The measurement was 0.76.

Sinclair: Were the measurements done with californium?

Auxier: No, on the spherical critical assembly.

Sinclair: Then what was the importance of the californium source in the mockup?

Auxier: The main purpose of that was to determine the angular distribution of the leakage. The logic for the Los Alamos use of a spherical assembly was that they could do a one-dimensional calculation. This made it simple to compare calculation and measurement but was also its weakness in that it did not show the differences between the nose and the sides and the tail of the Hiroshima and Nagasaki weapons. But it appeared to be valid to use the californium source and get the angular distribution of leakage from it. Integration over the solid angle, based on a polar angle measurement, gives a number within a few percent of 0.76.

Sinclair: Those weapons which you finally got to see and to use, when were they fabricated? Were they there from the beginning, and were they exactly the same?

Auxier: There is some debate about that, and I don't know. I wasn't in Japan with Dr. Friedell. There were notes about them and a record of their being put into a particular bunker where they had been since 1948. They had been assembled, I assume, in 1945 because soon after 1945 the weapons became more sophisticated.

Wyckoff: I am a little confused about what was known and what was done in getting the T65D, particularly with respect to the attenuation of the Hiroshima weapon. I understand that there were about 6 in. of steel around the weapon. Wouldn't one expect, then, quite a shift in the spectral distribution compared with the Nagasaki weapon?

Auxier: Certainly. We made no assumptions about the spectrum of the Hiroshima weapon until we had done the leakage measurements and Los Alamos had done the leakage calculation for the spherical assembly. Looking directly into the nose of Little Boy, one would see the same thing as looking directly through the spherical assembly. This assembly mocked up Little Boy from a head-on direction, and it had all the steel and the tamper and everything else as similar as Los Alamos could make it.

Wyckoff: My real question is, Wouldn't one expect a big difference in the spectrum from the two weapons and therefore a somewhat different attenuation in air for a given distance?

Auxier: We not only assumed but also knew that the spectrum in Hiroshima was softer than it would be from any other weapons that we had tested, but we assumed that at large distances—transported through air—the neutrons in the part of the spectrum below 170 keV would never reach there. We also assumed that the ^{14}N reaction was the dominant one for the low-energy neutrons and therefore, in terms of gamma production, they were of no consequence. Thus we are considering only the higher part of the spectrum, and it is clear that, no matter what the initial spectrum is, anything at large distances must ultimately approach the equilibrium spectrum that we see in all weapons; i.e., the neutrons, say, above the sulfur threshold have to dominate the relaxation length because the cross sections are smaller. They go farther and therefore, if they scatter down, produce the equilibrium spectrum that we always see. The real question is what to do about the low end of the spectrum, the soft part, initially. In our early work we threw it out. The Nagasaki weapon was different because the total thickness of the high explosive was such as to attenuate neutrons, and everybody's calculations show the same thing: that the total population of neutrons was extremely low and the fluences were low, but the spectrum would be propagated like that of a typical weapon. I don't think anyone debates the appropriateness of the spectrum we used in Nagasaki.

Wyckoff: What distance does it take to get this equilibrium? Is it certain that there is equilibrium at the distances we are interested in?

Auxier: No. That is the nub of the problem. At that time every spectrum we could see within two relaxation lengths, which in Hiroshima would be about 400 or 500 m, would be in equilibrium. We assume, with what we are doing with the spectrum, that it would take longer. The question is what distance to expect. The new calculations indicate very large distances, but, assuredly, equilibrium must be reached eventually because of the physics. If the distance is 100 miles, that is of no consequence; the only debate is whether equilibrium is reached in, say, four relaxation lengths, which is a long way. At that point the fluence is down to about 2% of its initial value, and we feel safe in assuming that equilibrium has been established. But you are correct that the distance poses a question.

Borg: My question has to do with the early time after explosion of either of the weapons. How well do calculations or measurements of neutron emissions based on mockups of the weapons mimic the effects of actual detonations? I am particularly concerned with the important neutron scattering and absorbing nuclei of hydrogen, carbon, and nitrogen in the high-explosive material. Certainly in the case of the Nagasaki weapon, at the time that the neutrons were being emitted, there had already been an implosion and all those nuclei were close in, which is geometrically much more effective than in a static mockup. What about the Hiroshima weapon? At the time that the neutrons were being emitted, where was the scattering and absorbing material and how well did a static configuration mock that up?

Auxier: Probably not very well. This is a question that we cannot yet answer precisely. We hope (as I have been hoping since 1956) that Los Alamos will finish these hydrodynamic calculations. Now, they are presumably within six or eight weeks. Full-blown hydrodynamic three-dimensional calculations are needed, in my opinion, to get the proper answer. The question can be answered qualitatively, to a certain extent, on the basis of many other measurements. In particular at Hiroshima, a simple time-dependent arithmetic calculation of how far the parts have moved, assuming a time scale at a few shakes (10^{-8} sec) per e-folding time, until peak power is reached, assuming that peak neutron emission is reached at approximately the same time, gives about 18 in., which would not have a major impact on the system. The people at Los Alamos, however, who know much more about this calculation, say that it could make a significant difference in both the leakage and the spectrum. This is a question most crucial to this symposium, and I hope to see calculations that will give an answer, one way or the other, in which I can have confidence.

Kaul: What is the magic of the 170 keV? Was that thought to be the threshold of the detector system involved?

Auxier: It was the threshold of the counter system we were using to make the measurements in Nevada in the houses, in the field, and in the leakage measurements with the weapon. This was a good, accurate system, and it was used throughout the whole program. The bias could be set at different levels, but with a high gamma-to-neutron ratio or with spurious noise from wind blowing through houses and things of this nature, usually the threshold was about 170 keV. We have ways to extrapolate under the bias, but it seemed abundantly clear in those days to everybody who worked on it or who had studied the situation that the low-energy neutrons just outside the fireball, anything below about 100 or 200 keV, would not go anywhere—would not contribute to the neutron dose or the gamma dose at large distances. I still feel that 170-keV neutrons coming out of a bomb cannot contribute to a dose at 1000 yards. Calculations such as yours indicate that they can contribute to the gamma dose—whether 3%, 5%, or more—but that is a different question. Nevertheless, at that time, right or wrong, that is what was done.

Kaul: You gave two numbers, the calculated number and the measured number, and the measured number was higher. One questions whether the cutoff on the experiments lacked sharpness and whether that might lead to counting some neutrons below 170 keV, thinking they were above 170 keV.

Auxier: The cutoff on the detector system wasn't as much at issue as the second part of your question, and I am sorry that I didn't address that earlier. One of the problems I alluded to was the complications of the signal-to-noise ratio and room return. The people who did this work were good, and they worried about the effect of room return on the part of the neutrons below 170 keV. That is where one sees the biggest effect. When they finished their results, we took the cutoff as 170 keV, and we took the fluence as that above 170 keV. They carried their calculations all the way down, and they did the best bin-by-bin comparison with the calculations that they could on the basis of a plotted spectrum. Looking at the data, we decided, since we got a match down to 170 keV, to use the value 0.76 neutron/fission as if all the neutrons were above 170 keV. That has no firm scientific basis, but it was all we could do at the time.

Friedell: Did you have any communication with the English group under Lord Penney? Immediately after the explosion, he entered with us. He was primarily interested in the blast pressure, but some members of his group were also interested in the distribution of radioactivity in the soil and in various objects. I know he took back various specimens that were crushed or modified by the blast so that measurements and calculations could be made. Have you gotten any information from his group which might be helpful in this assessment?

Auxier: I worked very closely with Sir William, now Lord Penney, both in the United Kingdom and here. He has put a lot of effort into this. He has had some of his senior groups working on the yield problem until fairly recently, and he believes as strongly as I that the yield is within half a kiloton of 12.5 kt, and that is as good a value as the data justify. He has not looked at the other data in a long time; when he did, he advised us that, with their scatter and uncertainties, the kinds of measurements made would not contribute to decreasing the uncertainties in our data. But his groups have truly done everything they could, everything we have ever asked them to do. He is a remarkable individual.

Revised Estimates of Neutron and Gamma-Ray Doses at Hiroshima and Nagasaki

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ABSTRACT

In the summer of 1980, Loewe and Mendelsohn of Lawrence Livermore National Laboratory (LLNL) released details of a complete but preliminary new free-field dosimetry at Hiroshima and Nagasaki, which was then finalized in the fall of 1980. This dosimetry was shown to have a major impact on the apparent relationship between leukemia incidence and radiation dose. The steps taken toward developing the LLNL dosimetry are discussed. These are (1) assessment of yields and computed bomb leakage spectra; (2) assumption of atmospheric conditions; (3) application of validation procedure to transport; (4) computation of prompt doses (source neutrons and source and secondary gammas); (5) evaluation and use of delayed (fission-product) gamma dose model; (6) comparison with in situ measurements; evaluation and reinterpretation of neutron activation dosimetry; (7) identification of origins of disagreement with T65 dosimetry; and (8) estimation of uncertainties.

In the summer of 1980, E. Mendelsohn and I, at Lawrence Livermore National Laboratory (LLNL), publicly released details of a complete but preliminary new free-field dosimetry at Hiroshima and Nagasaki (Loewe and Mendelsohn, 1980) which was then finalized in the fall of 1980 and submitted for journal publication (Loewe and Mendelsohn, 1981a). (Adjustments of about 20% were made.) This dosimetry was shown, in widely circulated preprints of that journal submittal, to have a major impact on the apparent relationship between leukemia incidence and radiation dose. A full description of that finalized dosimetry, along with additional confirming evidence, was presented at an international workshop last May and was also widely circulated as an informal document (Loewe, 1981). Since then a detailed article has been submitted for journal publication (Loewe and Mendelsohn, 1981b). Therefore this presentation will constitute elucidation of material that has previously been made available in several written forms as responses to requests for written explanation of this new dosimetry. It will follow closely the informal LLNL technical report D-81-10 (Loewe, 1981).

The following steps toward developing the LLNL dosimetry will be discussed:

- Assessment of yields and computed bomb-leakage spectra.
- Adoption of atmospheric conditions.
- Application of validation procedure to transport.
- Computation of prompt doses (source neutrons and source and secondary gamma rays).
- Evaluation and use of delayed (fission-product) gamma-ray dose model.
- Comparison with in situ measurements; evaluating and reinterpreting neutron activation dosimetry.
- Identification of origins of disagreement with T65 dosimetry.
- Estimation of uncertainties.

John Auxier's paper (in this volume) reminded me that about 15 to 20 years ago I was myself involved with the phenomenological approach to dosimetry.* I had occasion then, under an army contract, to review the field-test dose measurements for neutrons, gamma rays, and gamma-ray dose rate. Many of the problems that John mentioned were exceedingly real. I feel privileged to be around at this time and to be able to approach the dosimetry more from the analytical side. These intervening years have provided not only computers that produce good calculations but also the opportunity to check the calculations against improved experimental measurements.

In this paper I shall compare, for Hiroshima and Nagasaki [Figs. 1(a) and 1(b)], the neutron and gamma doses according to the old and the new estimates. The only biological end point we originally looked at for consequences was leukemia. The assumption that average values of building-shielding factors and phantom-attenuation factors do not change allowed a display of the effect of our newly calculated doses on biological end points. For leukemia, our newly calculated doses eliminate the distinction between the two cities [Figs. 2(a) and 2(b)]. Much discussion is going on about other biological end points.

The Japanese government is setting up three committees to review the issue. They will be emphasizing in situ data but will also carry out their

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*The remainder of this paper has been reconstructed by Margaret Dienes of Brookhaven National Laboratory from a tape recording made during the oral presentation. Therefore close reference to the pertinent tables and figures, which are reproductions of slides shown, is necessary to follow the text.

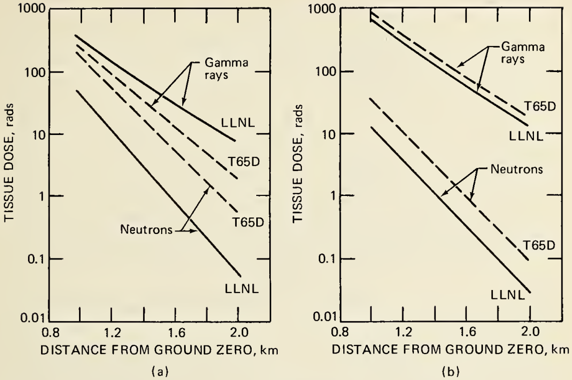

Fig. 1 Free-in-air doses (a) at Hiroshima and (b) at Nagasaki. LLNL, Lawrence Livermore National Laboratory. T65D, tentative 1965 dose. [From W. E. Loewe and E. Mendelsohn, Revised Dose Estimates at Hiroshima and Nagasaki, *Health Phys.*, 41: 663 (1981).]

own evaluation of what we come up with. I think it would be very good for us to cooperate fully with them in going forward in the estimation and evaluation of the dosimetry.

BACKGROUND

In the present context, the primary things to be emphasized in a description of the circumstances at Hiroshima and Nagasaki are the differences between the two bombs (Table 1). The chronology of neutron dosimetry estimates is given in Table 2. This represents a series of changes, not an abrupt dislocation. The results of Preeg (1976) and of Kerr [(1977); see Pace (1980)] are in parentheses because there are some difficulties in the calculations, which were of a preliminary nature and not documented.

Construction of the bone marrow dose is accomplished with the components listed below.

- Free-in-air, air-over-flat-ground kerma values.
- Terrain corrections.
- Building-cluster corrections.
- Building-attenuation factors.
- Phantom-attenuation factors.

Our work has been limited to free-in-air doses (i.e., kermas).

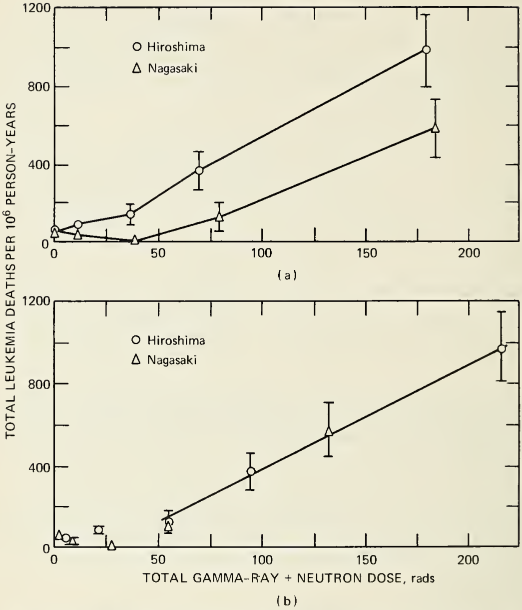

Fig. 2 Leukemia incidence vs. dose using (a) T65 data [From H. H. Rossi and C. W. Mays, Leukemia Risk from Neutrons, *Health Phys.*, 34: 355 (1980)] and (b) Lawrence Livermore National Laboratory data [the error bars on leukemia incidence represent one standard deviation based on the sample size. The uncertainties for dose values are not shown on part (b)].

TABLE 1

Comparison of the Two Atom Bombs Exploded

	At Hiroshima (Little Boy)	At Nagasaki (Fat Man)
Time and date	0815, Aug. 6, 1945	1058, Aug. 9, 1945
Height of burst, m	570	503
Yield, kt	15 ± 3	22 ± 2
Type of bomb	Little Boy (uranium, gun)	Fat Man (plutonium, implosion)
Humidity, %	80	71

TABLE 2

Chronology of Neutron Dosimetry Estimates at Hiroshima*

Reference	Rads
Wilson (1951)†	83
York (1957)†	21
Auxier et al. (1966)	10 (T65D)
Hashizume et al. (1967)	~9 (extrapolated)
Preeg (1976)	(~ 6.8)
Kerr [(1977); see Pace (1980)]	(~ 2.5)
Loewe and Mendelsohn (1980)	1.5 (current estimate)

*Doses are at 1.5-km ground range.
†As reported by Auxier et al. (1966).

The free-in-air estimate of kerma is the only topic that I will discuss at length here. Probably no building-cluster corrections need to be made since there were not enough substantial buildings crowded together sufficiently to have a combined effect. The building-attenuation factors are very important; they will be discussed later by other authors. The phantom-attenuation factors will also be discussed by others.

Some of the events that have been happening since 1965 to bring about dosimetry changes are outlined below.

PROGRESS SINCE 1965

- Improved estimates of atmospheric conditions, 1976, Los Alamos National Laboratory (LANL).
- Validated air cross sections, 1976, Lawrence Livermore National Laboratory (LLNL).
- Credible bomb output, 1976, Los Alamos National Laboratory (LANL).
- Validated air-over-ground calculational tools, 1978, Lawrence Livermore National Laboratory (LLNL).
- Comprehensive evaluation and modeling of gamma doses from field tests, 1966, IIT Research Institute (IITRI).

John Malik has worked to verify the atmospheric conditions at Hiroshima and Nagasaki, and I hope he will say something about that at this symposium. Air cross sections are important to our estimates. People have measured the pertinent cross sections carefully and have evaluated them. At LLNL some pulsed sphere measurements were done with liquid air, and comparisons were made with dose calculations. The Los Alamos National Laboratory (LANL) work on credible bomb output will also be discussed later by Paul Whalen (paper in this volume). The final item is a comprehensive evaluation and modeling of gamma doses from field tests that I was responsible for at Illinois Institute of Technology Research

Institute (IITRI) in Chicago, which were not yet available in 1965. I think some improvements can be made, and perhaps they have been made or at least are in process. Bill Scott (W. H. Scott, paper in this volume) will talk about some of them.

YIELD ESTIMATES

We had to assess the estimates of the yield that were being made to see whether we believed them and also to assess the bomb nuclear spectra [Fig. 2(b)]. Then we had to evaluate the gamma dose model on the basis of fission-product yields of weapons tests, a matter that I mentioned a moment ago. We then compared our new estimates with the in situ measurements available. This required reinterpretation, in one case, of dose inferences from the neutron activation measurements. Finally, we looked at the differences from T65D values, which had been the result of a thorough-going program.

The yield estimate we used for Nagasaki was the T65D number, 22 ± 2 kt; John Malik (see paper in this volume) will discuss the possibility of a smaller uncertainty (22 ± 1 kt). For Hiroshima, however, we adopted a value of 15 ± 3 kt, feeling that this is the best representation of the present state of the art (John Malik, paper in this volume, suggests a value of 15 ± 2 kt), but we also increased the error bars. The phenomenological numbers of Penney, Samuels, and Scorgie (1970) were the basis for the T65D yield, about 12.5 ± 2.5 kt. We feel that there is difficulty with those numbers. The effects used to calibrate Hiroshima against Nagasaki have a significant degree of subjectivity. The Hiroshima yields estimated by Penney and co-workers (1970) and by Malik (unpublished) are based on the Nagasaki yield (±10%) and depend on the ratio from effects in the two cities, i.e., the blast effects (house collapse, damage, gasoline cans) and thermal effects [flash burns on wood and tile and roughening of granite (±15%)]. The numbers are pretty good, but they are not as definite as one might like. A similar statement could be made about the one-dimensional calculations of yield, which are very difficult and sensitive to computational assumptions. They give a value around 19 ± 4 kt with a substantial uncertainty. We chose a number halfway in between, say 15 ± 3 kt, which is the same yield that John Malik independently thinks is about right on the basis of the effects data, and then increased the uncertainty to accommodate both the higher and lower values.

RADIATION TRANSPORT VALIDATION

We evaluated neutron and gamma radiation transport out to 2 km, which is quite a long distance. The pulsed spheres (laboratory quality, clean geometry) give a fairly good cross-section verification out to 1 km in air. Some integral comparisons were available previously (examples are given later in Figs. 3 and 4). In comparing the discrete-ordinate and Monte Carlo solutions, we were finally able to get very good agreement between the two, which led us to think that, if the Boltzmann equation is right (and, of course, we believe it is), then we are getting a correct solution and a proper representation of numerical values. We also compared one-dimensional and two-dimensional results, to make sure that we had treated the air-to-ground interface properly, and got good agreement away from the interface. Finally, there is the matter of representing the energy distribution of the neutrons and gamma rays with adequate resolution, as determined by the number of steps ("energy groups") in the calculational mesh.

Figure 3 shows an integral comparison. Our Monte Carlo calculation is compared with one of the Bare Reactor Experiment, Nevada (BREN) measurements just described by John Auxier (paper in this volume). The results show adequate agreement, which tends to give us considerable confidence in our ability to calculate. Figure 4 shows data from a bare reactor similar to the Health Physics Research Reactor (HPRR) but at a lower height of 14 m. Dose appears here as a function of range. Here the gammas are included; they were excluded in Fig. 3 because the source data were not available to us. Excellent agreement is seen between our cal-

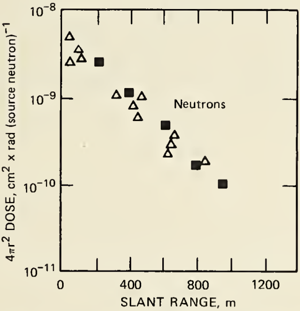

Fig. 3 Comparison of measured and calculated doses from the Bare Reactor Experiment, Nevada (BREN) Reactor. The BREN source was 8.2 m above ground. △, experimental. ■, Lawrence Livermore National Laboratory calculations. [BREN data from E. A. Straker, The Effect of the Ground on the Steady-State and Time-Dependent Transport of Neutrons and Secondary Gamma Rays in the Atmosphere, *Nucl. Sci. Eng.*, 46(3): 340 (1971).]

culations, the smooth lines, and points measured at the Ballistic Research Laboratory reactor in Maryland by workers from the Defence Research Establishment at Ottawa. These are high-quality and recent results (Robitaille and Hoffarth, 1980). The only problem is that the reactor is close to the ground as compared with the bursts at Hiroshima and Nagasaki, and it has a harder spectrum; but that is not at issue. What is at issue is our ability to calculate the doses, and the more ground you have, the more two-dimensional features you have. If we can calculate at this height, we can certainly do the calculations higher above the ground.

Several dose components need to be investigated: neutrons and gamma rays, both prompt and delayed (namely, to one minute or two, not longer). We looked at the delayed-gamma source but not at the corresponding fission-product contribution to neutrons. For both neutrons and gamma rays, prompt contributions come from bomb leakage directly out of the device. For gamma rays, however, these tend to be swamped out by secondaries resulting largely, although not exclusively, from neutron interactions with atmospheric nitrogen.

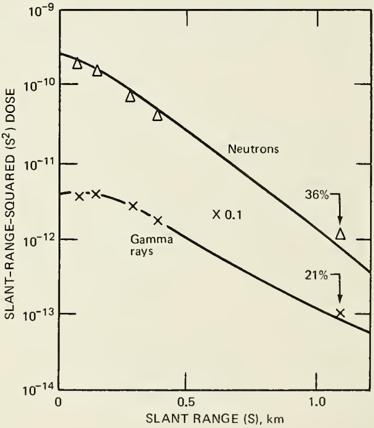

Fig. 4 Neutron and gamma-ray data from a bare metal reactor at 14 m. The curves represent calculated values; the points represent measurements by the Defence Research Establishment, Ottawa, at the Ballistic Research Laboratory. All the gamma-ray values have been lowered by the factor of 0.1 as a device to prevent the neutrons and gammas from intermingling confusingly.

NEUTRON SOURCES

Let me discuss the dose components one by one. For the prompt-neutron component, the leakage calculations are outlined below. [Paul Whalen (paper in this volume) will also discuss their credibility.]

NEUTRON LEAKAGE CALCULATIONS

Fat Man and Little Boy

- Ease of calculations for million-electron-volt neutrons.
- Modern computer technology: reliable calculations.

Fat Man

- Geometrically simple.
- Semiquantitatively predictable (spectral hardening).
- Fitting of dose lambda into pattern.
- Agreement with in situ measurements at 1 km.

Little Boy

- Converging sequence at LANL; preliminary confirmation at LLNL.
- Semiquantitatively predictable (piling up of downscatters).
- Fitting of dose lambda into pattern.
- Matching of bomb dose mockup measurement.
- Agreement with in situ measurements at 1 km.

For both bombs the important thing is deep-penetration transport of the neutrons, which is achieved only by neutrons exiting the source in the million-electron-volt range. These neutrons are relatively easy to calculate because they do not undergo many interactions as they exit the device and do not get into cross-section resonances. Also, modern computer technology has made major advances. The calculations are probably pretty good for both the devices.

Fat Man

For the Fat Man device specifically, the calculation is relatively easy because it can be done one-dimensionally and does not consume too much computer capacity. The result can almost be predicted. The high explosives surrounding Fat Man contain a lot of hydrogen, which has properties that are well known from reactor technology, where the phenomenon known as spectral hardening is well understood. Since most interactions are elastic, the neutrons suffer large energy losses, and because the cross section falls off as a function of energy, the lower energy neutrons are taken out of the spectrum more readily than the higher energy neutrons. Thus the spectrum actually changes from a fission spectrum to a slightly harder one. This can be seen in the LANL calculations on close examination and lends some credibility. There are not very many interactions; so the effect is not pronounced. Also, the dose e-folding length (λ) fits into a pattern. This length is not necessary in our estimates, but it is convenient in making comparisons. Consideration of different spectra—how they develop in passing through the air, and what dose lambdas they give—shows that the LANL estimates for Fat Man fit into that pattern very nicely and therefore cannot be very far wrong. Finally, our transport results agree with the in situ activation measurements, which I think are really good. This checks both transport and the spectrum, but the point here is the check of the source spectrum. (Note added: The preceding paragraph depends especially heavily on repeated reference to the cited text table, Neutron Leakage Calculations.)

Little Boy

Regarding Little Boy, similar types of statements can be made. A converging sequence of calculations has been made at Los Alamos and also some preliminary two-dimensional calculations at Livermore (not yet available); Paul Whalen (paper in this volume) discusses the calculations. One can predict semiquantitatively what to expect from Little Boy. Little Boy has no hydrogen and therefore no hardening effect. There is much metal and therefore much inelastic scattering. All the energy cannot be lost, as can happen in a scattering by hydrogen. There is a cascading down in energy from the very highest energies. Neutrons therefore tend to build up at the lower energies (but still in the MeV range), so that the lower energy ones increase in number relative to the higher energy ones. (Of course they all decrease in intensity.) This appears as a softening of the transport-determining part of the spectrum but is really a beefing up of the softer million-electron-volt range. Thus one would expect a much softer spectrum than that from a simple fission process, and the LANL estimates show that very well. Again, the dose lambda fits into a pattern (to be discussed later). John Auxier (paper in this volume) mentioned measurements on a mockup. We simply folded the LANL spectrum in with available flux-to-kerma factors and compared them. At the source they agreed very well. This is not a hard verification, but it is a necessary comparison.

The comparisons of spectra need to be put into perspective. At 2 km the difference between the two spectra is still seen (Fig. 5). There is no washing out of that initial difference in the source spectrum. At the high-energy end, there still is a distinctive difference between the two devices, although (we have normalized at thermal energies) there is not at the lower energies, which are controlled by the atmosphere. Figure 6 shows a fission spectrum for isolated nuclei and a spectrum from the HPRR for fission caused by putting many nuclei together in some kind of a core. The curve for Fat Man is actually higher than that for the bare core reactor, as

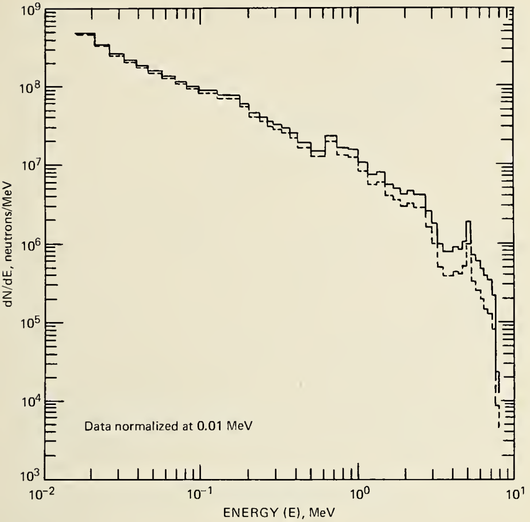

Fig. 5 Comparison of Nagasaki and Hiroshima neutron spectra at 2 km. ——, Nagasaki. – – –, Hiroshima. All the gamma-ray values have been lowered by the factor of 0.1 as a device to prevent the neutrons and gammas from intermingling confusingly.

expected, because of spectral hardening. The plot for Little Boy shows a drastically softer spectrum than that for the bare core. (Auxier's mockup measurements at Oak Ridge are similar in this respect but are very much softer than the calculated values and thus actually represent a more extreme estimate of the degree of softening of the spectrum.)

The dose lambdas, as mentioned, are not used or needed, but they are convenient for comparisons (Table 3). If we had a 14-MeV source spectrum—which we do not have, of course—then the attenuation length (the e-folding) in the Nagasaki atmosphere, for comparison, would be about 230 m. That is a very long distance. I have put it in as a bench mark. The calculated Fat Man value is 198, which is lower but not by a huge amount. The Fat Man value for T65D is also 198. The T65D-corrected value shown here was calculated with the assumption of zero humidity at the Nevada Test Site; there is some humidity, however,

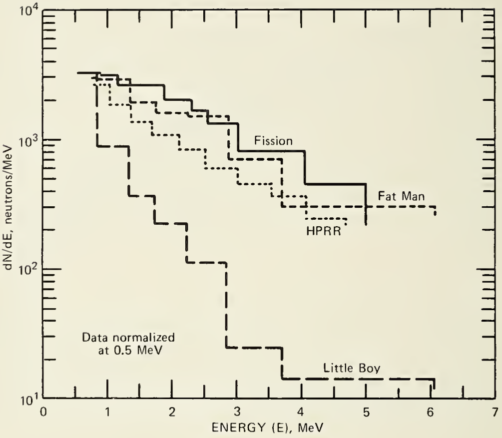

Fig. 6 Neutron output energy spectra.

TABLE 3

Dose Lambdas* for Nagasaki Atmosphere

Source spectrum	Attenuation length (λ),† m
14-MeV source	230
Fat Man	
Calculated	198
T65D: from Nevada Test Site and Bare Reactor Experiment, Nevada	198
T65D corrected for humidity	185
Bare metal reactor (calculated)	189
Little Boy (calculated)	153
Little Boy (T65D: by assumption)	198

*Dose lambdas give a rough idea of transport properties and are a handle on the source spectrum. Because they depend on distance, they have no intrinsic significance.

†For the dose e-folding.

and thus the Nagasaki value must be smaller than that obtained from test site data. (This is only a rough estimate.) Lambda shown for a bare metal reactor is a calculated value, and the result, 189, is a little lower than the 198 from Fat Man because Fat Man has a somewhat harder spectrum, as stated before. The value for Little Boy again reflects a very soft spectrum. These comparisons are thus semiquantitatively consistent.

NEUTRON-DOSE COMPARISONS WITH T65D

Table 4 shows some neutron-dose comparisons with T65D. T65D used the formula shown, which includes geometrical attenuation, the interaction with the atmosphere, and a necessary normalization factor. This is only an approximate expression, as everyone realizes, but it is worth emphasizing because the error due to the approximation amounts to perhaps 40% at 1 km in Hiroshima. The two values of G_0 compare well. The normalization factor G_0 was measured in the mockup. We folded our kerma factors in with the calculated LANL spectrum and obtained the same number. There is no problem there. The difference between our numbers and the previous numbers is due to two factors. One is the assumed lambda of 198, when it should be 155. (It is shown as 153 in Table 3 for an atmosphere consistent with other data shown in the table for Nagasaki, even though Little Boy was not exploded there.) This substantial difference accounts for almost all the difference between our doses and the T65D. The other factor is the formula inadequacy; the results of calculations

TABLE 4

Neutron-Dose Comparisons with T65D*

	T65D	Lawrence Livermore National Laboratory
	Hiroshima	
Normalization factor, G_0	6.98 (measured at mockup)	7.0
Attenuation length, λ	198 (assumed)	155
D (formula)/D (real)		0.6
	Nagasaki	
Normalization factor, G_0	13.0 (Bare Reactor Experiment, Nevada + calculation)	5.3
Attenuation length, λ	198 (Nevada Test Site measurements)	198

*Formula for T65D: $D = \frac{G_0}{S^2} e^{-S/\lambda}$

done with lambda (assumed to be 198), when compared with the results of the T65D formula, show about a 40% discrepancy as a result of the formula alone. For Nagasaki, Table 4 does not show D(formula)/D(real), but similar discrepancies result. The serious difference is in the intercept values, 13.0 vs. 5.3, which is difficult to account for since the exact construction of the T65D value is not documented. Since the lambda value is the same, none of the error is due to that. The remainder of the difference is due to difficulty with the formula.

IN SITU NEUTRON DATA

Some nice work has been done at the National Institute of Radiological Sciences at Chiba which was based on the possibility of estimating dose by measuring cobalt activation. Measurements were made, during urban renewal some 20 years later, on steel reinforcing bars inside structural-concrete pillars at several sites in Hiroshima and Nagasaki. A conversion factor is needed to relate those activation measurements to the dose outside, which is the desired information. Table 5 shows some estimates of such a conversion factor. For Hiroshima at a 1180-m ground range, Hashizume et al. (1967) give 318 as the number, M, used to convert the measurement, taken in counts per minute per milligram of cobalt, into the dose outside. (In Hashizume's paper, M = QN.) Our estimate of that number is 70. I am not absolutely sure why the discrepancy is so large, but I believe that it is because, in the estimation of M, it had to have been assumed that almost all the neutrons looked like those which

TABLE 5

Values of Activation-to-Dose Conversion Factor (M)

Impinging spectrum	M, rads/(cpm/mg)
Hiroshima at 1180 m (Hashizume constructed)*	318 (295)
Health Physics Research Reactor at 1 m (calculated)	280
Hiroshima at 1180 m (calculated)	70
Hiroshima at 1180 m	
Little Boy	70
Health Physics Research Reactor	100
Fat Man	110

*Hashizume et al. (1967).

Note: Constructed values of M used a "slow" component that was too small. Activation is a valid dosimeter to first order (±30%), for locations at a distance, and for fission bombs.

come from the HPRR. My conclusions are (1) that Hashizume's M was based on measurements using a neutron source which simply had too little thermal component but (2) that the activation measurements made in the pillars provide a relatively good dosimeter (a) if one accepts a first-order estimate, say ±30% (and that simply comes from comparing values shown here); (b) if the estimates are made only at some distance from a source point, say most of a kilometer; and (c) if there is no component of very hard neutrons (e.g., 14 MeV). With these limitations, which are satisfied in the present application, the activation measurements do have great significance.

The measured values of cobalt activation at Hiroshima and Nagasaki are very similar (Table 6). The calculation was difficult, and we were unable to do it exactly; it was an approximation. We also calculated a two-dimensional adjustment factor that is reasonably good but not exact; both the approximate one-dimensional and two-dimensional values are shown. There is some added uncertainty here because we do not know the concrete composition; our colleagues in Japan are looking into that now. However, I have done some calculations varying the concrete composition rather drastically, and, unless it is extremely extraordinary, e.g., containing huge amounts of boron, the composition does not affect the results very much. Since we do not expect that, I consider these to be fairly good confirmation of our results.

TABLE 6

Cobalt Activation* by Neutrons

	Hiroshima at 1180-m range	**Nagasaki at 1030-m range**
Measured	5.3	5.4
Calculated	8.1 (~6)†	4.5 (~3)†
Ratio	1.5 (~1.1)†	0.8 (~0.6)†

*Unit: one million atoms of ^{60}Co per milligram of ^{59}Co.

†Value in parentheses is a two-dimensional approximation.

SECONDARY GAMMAS

The prompt secondary gammas are obtained directly from the same calculation as the neutrons (Fig. 7). The secondary gammas amount to almost all the prompt portion of the gamma dose (80 or 90%); the gammas coming directly from the device contribute about 10%. The source

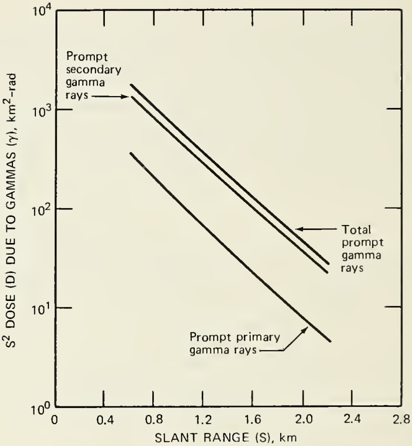

Fig. 7 Nagasaki prompt gamma-ray kermas.

data for the source gammas are from the LANL calculations. Both prompt components of the gammas were calculated in the same way—with different cross sections—as the neutrons. In the pulsed sphere measurements, we also checked the gamma cross sections, and the values used seem to be about right.

PROMPT FISSION-PRODUCT GAMMAS

The IIT Research Institute fission-product gammas are based on a model (work done in 1966) which is

- Time dependent: Cloud rise. Hydrodynamic enhancement. Optical depth transport. Pressure, density, yield dependent.
- Empirical correction to source strength (modern support), 40%.
- Absolute dose *rate* comparisons: Various ranges at 18 events from 9 test series.
- Absolute dose comparisons: Various ranges at 57 events from 10 test series.

Hydrodynamic enhancement simply means that the sweeping away of air by the blast changes the effective optical depth. The empirical correction to source strength has had some modern support that I hope Bill Scott (paper in this volume) will discuss. When all these ingredients are put into the modeling of the field test data, the results are rather good. They are almost always within a factor of 2, and, looked at together, suggest 30 to 50% confidence across the board. That is for all ranges, 18 events from nine series of tests, for absolute dose rate, made by different people with entirely different measurement instruments. The dose rate measurements at 57 events in 10 test series involved various bombs in different years and were measured by different people with different instruments. Thus, overall, we have high confidence that the fission-product gamma dose is about right.

The question is, What does "about" mean? The Ranger Fox test, done in the early 1950's in Nevada, was similar to the Nagasaki burst. We used the fission-product model that I just mentioned, which must be about right, generally speaking, to see exactly how well it does in this particular case. We picked up the prompt contribution calculated last year and added to it the fission product from the 1966 IITRI model (Loewe et al., 1966). Two slant ranges are shown in Table 7. [The data for 1105 m are given in a report now publically available (Los Alamos Scientific Laboratory, 1952), and all the details appear in a paper to be published in *Nuclear Science and Engineering* (Loewe and Mendelsohn, 1981b). The numbers given here mean that the estimate comes to within 4% of the measured value.] This agreement at both ranges is fortuitously good, but it gives us considerable confidence in the fission-product contribution, which is about half of the total gamma dose.

TABLE 7

Gamma Dose at Ranger Fox Test*

Slant range, m	Measured dose, rads	LLNL dose,† rads
1105	959	926
1829	40	39

*This Nevada atmospheric test was similar to the Nagasaki explosion.

†The LLNL dose is prompt calculated by LLNL plus fission-product debris from the IIT Research Institute model.

TOTAL GAMMA-DOSE COMPARISONS

Figure 8 shows comparisons of extrapolated and calculated data for total gamma dose. Within ~1 km in the slant range, the extrapolated data would not be very bad at Nagasaki—although they would be somewhat in error—but at Hiroshima the departure would be fairly substantial. Of course, the extrapolation also depends on getting the slope rather exactly. The point is, if you only know values with 1 km, you really cannot get the right answer at 1.5 or 2 km.

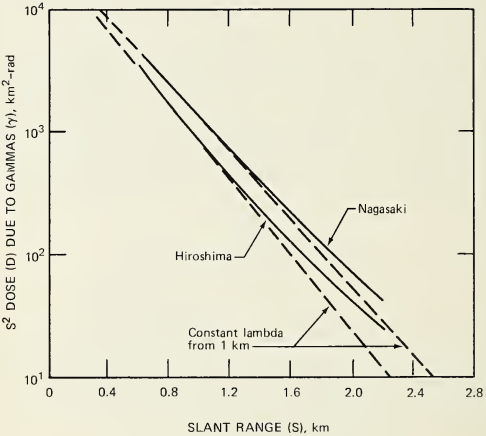

Fig. 8 Total gamma-ray kermas. Extrapolation from 1 km would have been in error.

Figures 9(a) and 9(b) show in situ results obtained at Nagasaki and at Hiroshima, respectively, by Hashizume et al. (1967) and by Ichikawa, Higashimura, and Sidei (1966) when they measured roof tiles and glazed facing brick with a thermoluminescence dosimetry (TLD) technique. These results show generally good agreement (but cannot be extrapolated out to 2 km). I am impressed that one can do that well with unprepared samples from rooftops and the like. Also shown are the T65D and LLNL data; within 1 km, all four data sets agree reasonably well, with no in situ data beyond that and divergence in the two estimated values beyond 1 km.

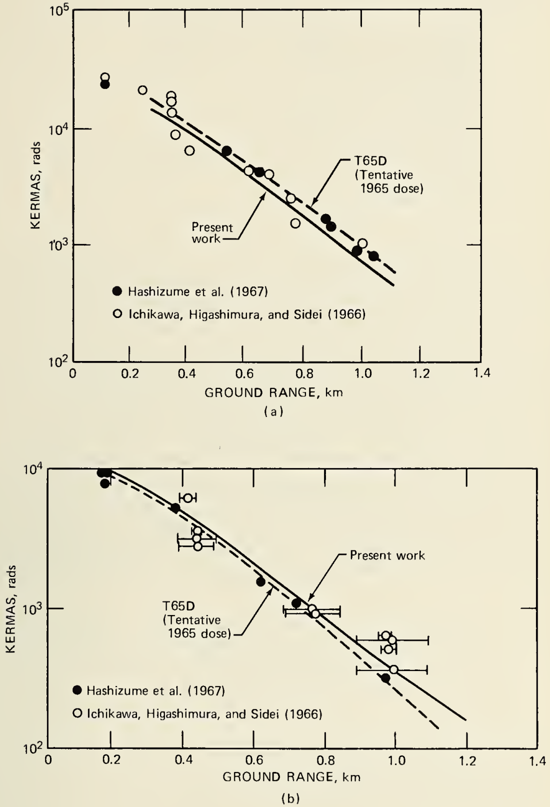

Fig. 9 Gamma-ray kermas (a) at Nagasaki and (b) at Hiroshima.

UNCERTAINTIES IN DOSIMETRY

The following uncertainties in our results must be considered:

- Yields (±10% at Nagasaki; ±20% at Hiroshima).
- Delayed neutrons (<100% at 1 km; negligible at 1.5 km).
- Fission-product gamma.
    Dependence on isotopes (10 to 15%).
    Dependence on hydrodynamics (10%?).
- Bomb leakage (30 to 40%).
- Bomb anisotropy, air and ground composition, cross sections (15%).

- Overall uncertainty: a factor of <2.
- Uncertainty in uncertainty: a factor of 2.

Those in the yields have been quoted as 10%, but we think they are probably twice that, or 20% at Hiroshima (Fig. 8). For delayed neutrons we do not believe there is anything like 100% contribution at 1 km, but we would like to be able to prove that, although we have not done the necessary calculations yet. We have been able to show that the contribution is negligible at 1.5 km, which is perhaps more interesting. In the case of fission-product gammas (which Bill Scott discusses in his paper in this volume), there is a dependence on isotopes, which we judge—on the basis of preliminary information—to be about 10 to 15% in total dose at Hiroshima and Nagasaki, and a different dependence on hydrodynamics, which we guess might be 10%. Regarding bomb leakage, I do not know just what uncertainty to ascribe, but it cannot be either very large or very small; perhaps Paul Whalen (paper in this volume) will bring us up to date. There is an uncertainty to the cross sections, which we estimated at perhaps 15% at most, and there is a dependence on air and ground composition.

Bomb anisotropy has a real effect, but it is rapidly washed out with distance. John Auxier (1977) made measurements of angular distribution around the Little Boy mockup. They showed about a 4-to-1 or 5-to-1 variation. This gives an idea of the angular distribution outside the Little Boy device and shows it to be quite anisotropic. Both fluence and dose were measured, and there is hardly any difference in the degree of asymmetry (see Table 8). Since the dose is calculated with emphasis on high-energy neutrons, this minor difference indicates that there is not a very strong energy–angle coupling, and that, in turn, means that the effect would not be very great if one took into account, in detail, exactly how the energy spectrum shifts from the waist to the pole (Table 8).

That being the case, one can do an approximate calculation by using either the fluence or the dose since they are essentially the same. The isotropic "dose" shown in Table 9 is what I have been discussing. The data

TABLE 8

Measured Values of Leakage Anisotropies from Little Boy Mockup

Polar angle, degrees	Relative neutron fluence	Relative neutron kerma	$1.27 \frac{\text{Kerma}}{\text{Fluence}}$
0	1.1	0.9	1.04
18.5	1.3	0.9	0.88
45	2.6	1.5	0.74
71.5	3.7	2.7	0.93
90	4.2	3.6	1.09
108.5	4.6	4.1	1.13
135	4.7	4.3	1.16
161.5	3.5	2.3	0.84
180	1.7	1.6	1.19

Note: The factor 1.27 is chosen to allow assessment by inspection of the variations in the ratio of dose to fluence.

TABLE 9

Effect of Anisotropic Neutron Source on Ground Doses*

Ground range, km	Anisotropic "dose"/ isotropic "dose"	
	Neutron	Gamma
0	0.78	0.91
0.5	0.86	0.96
1	0.96	0.98
1.5	0.99	0.99

*The roughly 15° off-vertical cant of the falling bomb was ignored in the calculation.

shown for the anisotropic "dose" required repeating the calculation using a source that has a 5-to-1 asymmetry, as in Table 8. The effect of anisotropy at the hypocenter is 22% for the neutrons and 9% for the gammas, and, at a ground range of 1 km, it is 4% and 2%, respectively; that is, the effect is swiftly washed out. Thus, for the dose at large distances, where many of the survivors were located, it does not matter. (Nonetheless it is something that we can be interested in as a way of verifying our calculations.)

CONCLUSIONS

Accepted doses are seriously wrong (at 2 km, × 9 Hiroshima neutrons and × ¼ Hiroshima gammas). LLNL doses are about right (well-founded construction consistent with or supported by pertinent data). We think our overall uncertainty is something less than a factor of 2. It depends on who is speaking and how formally, and the mood he is in, as to how much less than a factor of 2. I tend to be on the optimistic side. There is a considerable uncertainty in that estimate, shown as a factor of 2, but I do not mean that it is likely to be poorer by a factor of 2, only possibly half as large an uncertainty. My personal feeling is that it may be somewhere in the general vicinity of a factor of 1.5, which is a reasonable uncertainty, all things taken together. [Note: See my remarks during the General Discussion, page 274.]

ACKNOWLEDGMENT

I am very pleased to acknowledge the splendid work done by Margaret Dienes of Brookhaven National Laboratory, who reconstructed and edited this text from a recording of the oral presentation.

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DISCUSSION

Eisenhauer: Have you resolved the error, I think it was quoted originally as a factor of ⅔, in the effects manual called EM-1? Has that been corrected, or what is its status?

Loewe: The EM-1 manual that we used in our results of August 1980 simply had some wrong numbers. First, as I was told informally by Jess Marcum, some changes were injected into the original formula to make it simpler. Looking at the equations, I see a square where it should not be, and that is simply an error. Second, the same people said that there is no justification for the 40% empirical correction we had made at IITRI. Both of these problems were remedied in October 1980 simply by using the original IITRI formulation.

Bond: To what degree do you regard what you have done as a finished piece of work, and to what degree do you regard it as a way point for something more refined? If it is the latter, what do you consider to be the most important factors remaining to be ironed out?

Loewe: That is a loaded question. The uncertainties that I quoted indicate that this should not be regarded as finished work. I judge that the uncertainties can be reduced substantially by further work. Precisely that point will be addressed by Dr. Mendelsohn (Mortimer), for example, in terms of what the biology requires. Thus we are at a way station. However—though not everyone would agree—I think our results are good enough to be used, but with due caution since uncertainties remain. I believe our results are reliable, however, and we are not at all likely to see big changes. The energy spectrum is probably the largest source of the difficulties, although fission-product gammas should also be addressed. The greatest dose uncertainty overall, as opposed to our free-field kermas, is probably due to the difficulty in determining the building-shielding factors. We have not investigated this, although Jess Marcum has. Bill Woolson will discuss this. I would be reluctant to invest those building-shielding numbers with high credibility until more work has been done since they are largely surmise on Jess's part. However, I think the surmise is an excellent one. Factors of about 1.6 probably need to be introduced into the gamma portion of the building-shielding factors; these represent, by and large, by far the largest single adjustment that I expect to take place.

Borg: Will the difference in the shielding be due in large measure to the difference in the projected energy of the incident gammas? You have projected a greater fraction of nitrogen-capture gamma rays and hence a harder and more penetrating gamma spectrum coming in than was assumed in the T65D estimates. Is that right?

Loewe: I do not know the answer to your second question. I am sure that, by having a slightly different gamma spectrum, you will have somewhat different shielding and building attenuation factors. That does need to be looked into. I doubt that the factor will be very large. Jess Marcum suggests an adjustment of 1.6, and Bill Woolson will discuss the basis for that. However, it has to do with the deficiencies in interpretation, if Jess's surmise of the Hardtack tests, on which the numbers were based in the first place, is correct. (In a word, there were too many neutrons at Hardtack.) I regard it as an enlightenment possibly triggered by our results, since we emphasize the low proportion of neutrons at Hiroshima and Nagasaki, and possibly not—maybe Bill can clear up just what the motivation was. This really has nothing directly to do with our results.

Wyckoff: I think you said that the experimental determinations showed that the neutron spectrum of the Hiroshima weapon fell off with energy. Was that just the leakage, or was that after transport through air?

Loewe: That is leakage.

Wyckoff: The points are whether there has been an experimental determination of a falloff in the energy spectrum after attenuation by steel and whether the energy spectrum reaches equilibrium. Have you checked that?

Loewe: Yes, to both questions. I looked into equilibration. It was at Hiroshima, and it was one-dimensional, because that is easier to do. There I found that lambda went up from 155 and kept on increasing up to 160, 165, and 170, out to larger and larger distances. As I recall, the 170, which is not the whole distance traversed, was somewhere around 2 km, and as near as I could tell, it was continuing to rise. I think someone at Oak Ridge, probably Joe Pace, has looked into the matter, and he may have a comment on what happens at 3 km.

Wyckoff: You gave some relaxation lengths; at what distances were those measured?

Loewe: At about 700 or 800 m. I did not know where the standard point of measurement was in the BREN series, but I guessed from the data that it was right about there because further out the data were bouncing around, and closer in one would run into difficulties with buildup. I picked that range to compare, but I believe any other range would give a similar comparison.

Wyckoff: I was interested because I got a relaxation length of about 170 at about 2 km.

Loewe: That is about what I got.

Malik: There are two major components to gamma-ray dose: neutron capture, which has about a 70-msec period, and fission-product radiation, which is in the second domain. Since both are long-time components, one would expect the mean free paths to be almost independent of weapon design except for the ratio of total neutron output and fission-product contributions. Why is your mean free path for gamma rays for Hiroshima so short?

Loewe: The mean free path for the fission-product component ought to be about the same in both cities. I have not looked into exactly how close they are. The secondary component, however, is different in the two cities. For Little Boy the neutron spectrum is soft in the high million-electron-volt range, but the overall spectrum is not quite so drastically shoved down in energy as it is for Fat Man. Thus that big clump of really low-kilovolt neutrons is not available for immediate capture. Instead, the Little Boy neutrons go out and form a distributed source. The neutron spectrum for Fat Man, which I do not have here, shows a big bulge at very low energies, and the neutrons get absorbed right away, forming a point source. Little Boy does not have that problem; therefore the neutrons produce secondary gammas at a greater distance and form a distributed source, and the source location has a major effect on the lambdas. Remember, too, dose lambda is artificial, not fundamental, and varies with range.

Malik: If the distributed source is small compared with kilometers and the neutron-capture component is growing in importance in the ranges of the order of 1 km, I am a little surprised that both Little Boy and Fat Man cannot be approximated by a point source, at least as a first-order approximation.

Loewe: I would argue that the neutron-capture component is about 50% in round numbers. I agree with you that the fission-product contribution is a point source. I do not know just how big a contribution to the dose at 2 km is developed from gamma rays formed in the immediate vicinity compared with gamma rays formed all the way back at an approximated source, but I do know that you get a rather hefty advantage on a gamma ray if it is formed relatively close to your detector point.

Sinclair: You did not mention the question of possible future agreement or disagreement between calculations and activation data. It seems to me that a great deal of our confidence in calculations is going to depend on whatever experimental measurements we can get to confirm them, and your agreement between the activation data and the calculation is based on certain assumptions, many of which depend on the spectrum. I think that Dr. Maruyama mentioned at the Minneapolis meeting that he thought the interpretation of the data depended critically on the assumptions about the spectrum. How do you see this situation developing in the future? What can we do about the activation data? Is there any more we can do to get experimental confirmation?

Loewe: In terms of agreeing with the activation measurement itself, which is the only legitimate neutron measurement made in situ, no assumption is required. We simply agree. Los Alamos does the output calculations. We do the transport calculation. An activation is measured, and there is a minor approximation involved of 10 or 20%. The result compares well with the measurements without interpretation or assumption. The discussion about assumptions and spectrum deals with the transformation of a particular activation to a dose up in front of the concrete pillar. There I claim it is not an assumption but rather a sensitivity-study decision. That is a different matter, and it depends on how you like 30% uncertainty in your dosimeter. Turning to your second question, there are other ranges at which activation has already been measured by Hashizume and his coworkers. We have not calculated those yet, because it gets harder and harder to carry out the calculations as you go in, and probably less interesting as well, but nevertheless the comparisons should be done. Each of the three committees being formed in Japan has a slightly different purpose. The third committee, which is not yet official, seems to have a particular interest in in situ measurements. They are trying to think of anything that can conceivably be measured, and in particular they are looking for rings that protrude from building walls for window washers to hook onto. Apparently at least one is available, and certain members of the third committee are measuring activation in that. This is a measurement of thermal neutrons; it may or may not be an improvement on Hashizume's measurements. People in Japan are also thinking about the possibility of measuring europium activation in the soil. They are also working with sulfur. I have been unable to get the sulfur data in terms that I can calculate directly (counts per minute in a fixed geometry). I can get dose equivalent, which I do not believe, because it again involves an assumption about conversion. I suppose the direct data are available somewhere, and somebody ought to do a very careful calculation. The data tend to be at a very limited range, I think out to 1 km . . . .

Kerr: Yes.

Loewe: . . . and those sulfur measurements should be looked into also.

Levin: You mentioned some two-dimensional calculations that you had done; were these leakage calculations? Were you and Los Alamos doing about the same thing so that yours is part of a larger computation? You passed over that quickly.

Loewe: I passed over it quickly because the results are preliminary and not yet written up, although we have already convened an in-house committee to review them, and the committee agreed that they are pretty good. Los Alamos is somewhat in a state of flux, and Paul Whalen is going to tell you the status of their calculations. I think that the Los Alamos spectrum results should be believed for reasons previously stated and also because our preliminary leakage results are fully two dimensional, quite independent of Los Alamos, and agree well in the million-electron-volt range of interest to us here. I do not understand your question about a "larger computation;" Los Alamos calculated the spectra one dimensionally in 1976 and is now recalculating Little Boy in two dimensions, whereas we did our own check calculation in two dimensions this year just because this device is so important.

Findings of a Recent Oak Ridge National Laboratory Review of Dosimetry for the Japanese Atom-Bomb Survivors

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ABSTRACT

More detail than was previously available on the leakage spectra of neutrons from the Nagasaki and Hiroshima weapons was provided by calculations made at the Los Alamos National Laboratory in 1976. Several neutron-transport calculations using these data have predicted significantly less neutron exposure in Hiroshima than the current radiation-exposure estimates for survivors designated as T65D (or tentative 1965 doses). The difference was extremely important since recent studies using the T65D estimates have predicted a very large leukemia risk for neutrons at low exposure levels in Hiroshima.

A review of the dosimetry for the atom-bomb survivors, requested by the National Council on Radiation Protection through the U. S. Department of Energy, was started in late 1979. Several early studies aimed at resolving the discrepancies gave ambiguous results. This was especially true of sulfur activation by fast neutrons which was more easily related to neutron leakage from the weapons and to neutron exposure of the survivors than thermal neutron activation of other materials. A breakthrough was provided in mid-1980 by information on sulfur activation found in a Japanese report on radiation surveys made in the two cities immediately after the bombings. This information quickly resolved many of the ambiguities between the newer neutron-transport calculations and the older T65D estimates.

Some findings of the review are that the neutron exposures in Hiroshima were probably less than the T65D estimates by factors varying from about 4 at a ground distance of 1000 m to 8 at 2000 m, and the gamma-ray exposures were greater than the T65D estimates starting at about 1000 m and were probably larger by a factor of about 3 at 2000 m. In Nagasaki the situation was reversed with respect to gamma rays, and the T65D estimates were higher, but the differences were small (i.e., about 20% at 1000 m and 30% at 2000 m). As a result, it now appears that leukemia and other late effects at lower exposure levels in Hiroshima were due largely to gamma rays rather than to neutrons. This, however, may not be true at higher exposure levels in Hiroshima.

Any reanalysis of data on late effects among the atom-bomb survivors should be regarded as highly speculative until some other important issues have been investigated in more detail. These issues include the anisotropy in neutron leakage from the Hiroshima weapon, the energy yield of the Hiroshima weapon, the shielding factors for houses, and the organ-dose factors for the atom-bomb survivors.

The epidemiological studies of the atom-bomb survivors by the Radiation Effects Research Foundation (RERF), formerly the Atomic Bomb Casualty Commission (ABCC), provide invaluable quantitative data on the late effects of radiation exposure (Committee on the Biological Effects of Ionizing Radiations, 1980; United Nations Scientific Committee on the Effects of Atomic Radiations, 1980). Because of the importance attached to these data in the assessment of radiation-exposure risks, an up-to-date review of the dosimetry for the atom-bomb survivors was recently requested by the National Council on Radiation Protection (NCRP) through the U. S. Department of Energy (DOE). The expert assistance of others in the review has been provided at the request of the NCRP by both DOE and the U. S. Defense Nuclear Agency (DNA).

A primary objective of the review was to determine whether the large leukemia risk for neutrons found at low exposure levels in Hiroshima by Rossi and Mays (1978) and by Ishimaru, Otake, and Ichimaru (1979) was real or whether it was the result of a bias in the current radiation-exposure estimates for survivors, which are designated as T65D (i.e., tentative 1965 doses) (Auxier, 1977). The potential for a bias existed because the two weapons dropped in Japan were of entirely different design, content, and construction (Brown and MacDonald, 1977; Groueff, 1967). Some radiation-exposure data were available from test firings of Nagasaki-type weapons, but no other Hiroshima-type weapon was ever fired except the one combat drop in Japan.

The Hiroshima weapon, code named Little Boy, was a massive gun-assembly device (Fig. 1) that used a small propellant charge to shoot one piece of ^{235}U down a barrel into a second piece to form a critical mass at the time of explosion (ATE) (Glasstone and Dolan, 1977; Thomas and Witts, 1977). The weapon was exploded about 8:15 a.m. on Aug. 6, 1945, over the center of the city [Fig. 2(a)] at a height of 580 m (or 1900 ft) (Hubbell, Jones, and Cheka, 1969; Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki, 1981). The Nagasaki weapon, code named Fat Man, was an implosion-type device (Fig. 1) that used thick charges of high explosive (HE) to compress a subcritical mass of ^{239}Pu (and a tamper of ^{238}U) into a critical mass ATE (Glasstone and Dolan, 1977; Lamont, 1965). It was exploded about 11:02 a.m. on Aug. 9, 1945, over the Urakami Valley in the northern part of the city [Fig. 2(b)] at a height of 503 m (or 1650 ft) (Kerr and Solomon, 1976; Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki, 1981).

The radiation exposure decreased rapidly with increasing distance from the burst point of a weapon, due in part to geometrical attenuation and in part to atmospheric attenuation (Abbott, 1973). Thus one important

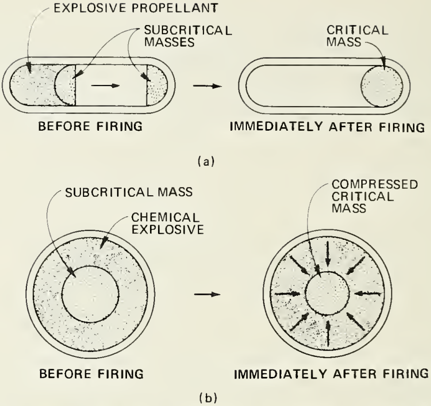

Fig. 1 Schematics illustrating the principles of (a) Little Boy, a gun-assembly nuclear device, and (b) Fat Man, an implosion-type nuclear device (Glasstone and Dolan, 1977).

parameter in estimating a survivor's radiation exposure is distance from the burst point (or air-zero point) of the weapon (Fig. 3). The distance R from air zero for a flat ground surface is given by the square root of $d^2 + H^2$, where H is the weapon's burst height and d is the survivor's distance from ground zero. If the terrain near ground zero is uneven, as in Nagasaki, then the slant distance R is equal to the square root of $d^2 + (H - h)^2$, where h is the survivor's elevation relative to ground zero. Shielding by uneven terrain and surrounding structures is another important parameter that must be taken into account in estimating a survivor's radiation exposure (Fig. 4) (Arakawa, 1960). The structural shielding conditions reported by survivors who were close to ground zero ATE are subdivided into several categories in Table 1 (Kerr, 1979a; Davis, Baker, and Summers, 1966).

TENTATIVE 1965 DOSES (T65D)

Most of the survivors were exposed inside residential wood-frame structures (Table 1), and the uniformity of Japanese house construction made a definitive dosimetry study feasible (Noble, 1968; Auxier, 1977). The current radiation-exposure estimates take into account a survivor's shield-

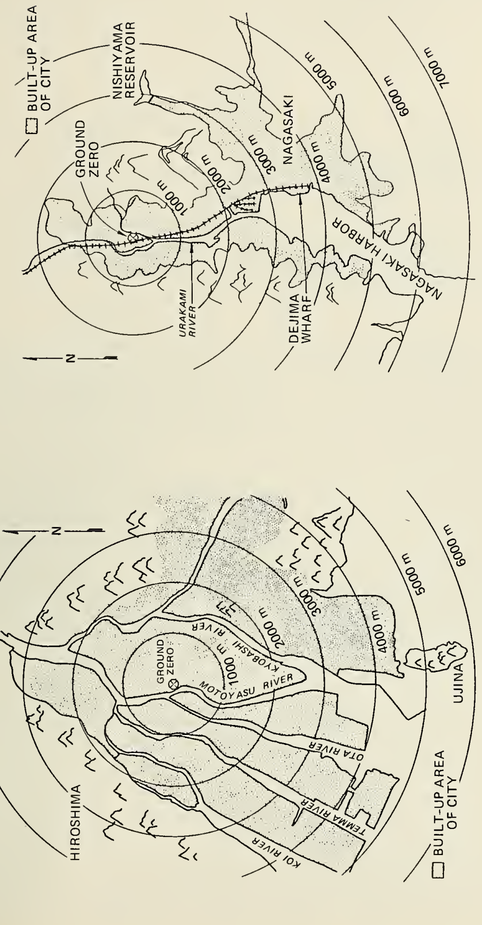

Fig. 2 Map showing built-up areas and location of ground zero (a) in Hiroshima and (b) in Nagasaki.

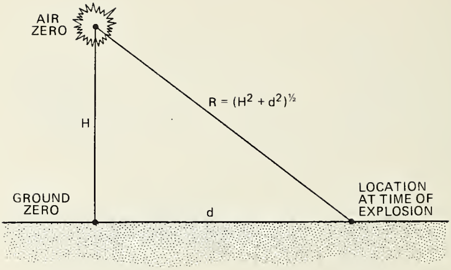

Fig. 3 Schematic illustrating the relationship between the height of burst (H) above ground, the survivor's distance (d) from ground zero, and the slant distance (R) from the burst point, or air-zero point, of the weapon.

ing by surrounding structures primarily through the house-shielding factors developed by Cheka et al. (1965) and a survivor's distance from ground zero through the tissue-kerma-vs.-distance relationships developed by Auxier and co-workers (Auxier et al., 1965b, 1966). These estimates are designated as T65D (Milton and Shohoji, 1968) to distinguish them from some earlier radiation-exposure estimates for survivors designated as T57D (or tentative 1957 doses) (Arakawa, 1960; Ritchie and Hurst, 1959; York, 1957). For the Fat Man device, some radiation-exposure data were available from weapons tests, and these data were used in constructing the T65D tissue-kerma-vs.-distance relationships for Nagasaki. Several duplicate Fat Man devices were fired during the Trinity test in July 1945 and the Crossroads Able and Baker tests in 1946 (Wilson, 1956; Auxier, 1977), and results of these tests indicate that the energy yield of the Nagasaki weapon was equivalent to 22 (±2) kt of TNT (Malik, 1954, 1980).

There were no data from weapons tests in the case of Little Boy, and the T65D tissue-kerma-vs.-distance relationships for Hiroshima were constructed by using data from several of the most nearly appropriate weapons tests and data from reactor experiments (Auxier et al., 1965b, 1966). One reactor experiment at Los Alamos Scientific Laboratory (LASL) using the Ichiban critical assembly provided data on neutron leakage from Little Boy (Auxier et al., 1965a; Thorngate, Johnson, and Perdue, 1966), and another reactor experiment at the Nevada Test Site (NTS) using the Oak Ridge National Laboratory (ORNL) Health Physics Research Reactor (HPRR) provided data on the penetration of neutrons (and gamma rays) in an air-over-ground geometry (Haywood, Auxier, and

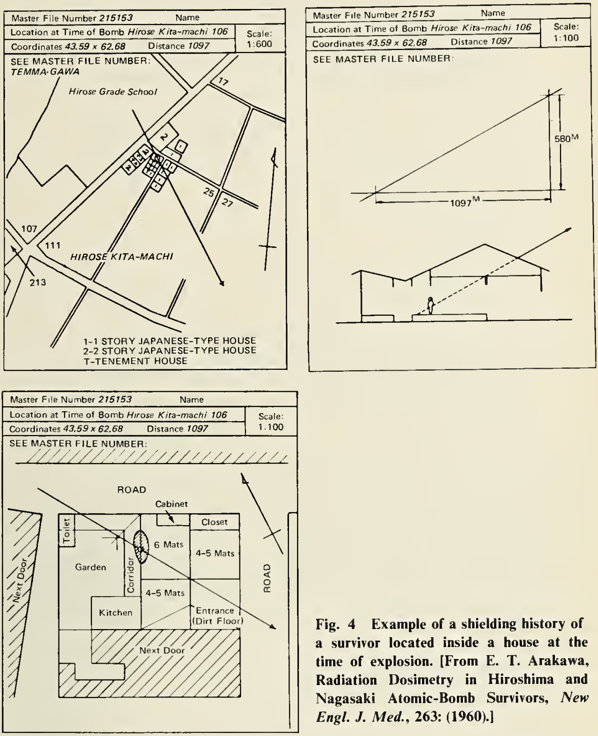

Fig. 4 Example of a shielding history of a survivor located inside a house at the time of explosion. [From E. T. Arakawa, Radiation Dosimetry in Hiroshima and Nagasaki Atomic-Bomb Survivors, *New Engl. J. Med.*, 263: (1960).]

Loy, 1964; Haywood, 1965). The resulting tissue-kerma-vs.-distance relationships were normalized to an estimated energy yield of 12.5 (±2.5) kt for the Hiroshima weapon. Later studies by Penney, Samuels, and Scorgie, (1968, 1970) and by Auxier and associates (Auxier et al., 1968; Auxier, 1977) reduced the estimated probable error to ±10% (or about 1 kt).

The T65D tissue-kerma-vs.-distance relationships were found to agree in general with results of independent studies by Hashizume et al. (1967) of the Japanese National Institute of Radiological Sciences (JNIRS) and by Ichikawa, Higashimura, and Sidei (1966) of the University of Kyoto (Fig. 5). The gamma-ray exposures at various ground distances in both

TABLE 1

Approximate Percentage of Survivors Reporting Various Exposure Conditions at Distances from Ground Zero of <1600 m in Hiroshima and <2000 m in Nagasaki

Exposure conditions	Percentage of Hiroshima survivors	Percentage of Nagasaki survivors
Outdoors		
Unshielded	10	5
Shielded	10	10
Indoors		
Wood-frame structures	75	65
Concrete and other structures	5*	20†

*Mostly heavy concrete or brick buildings.

†About half were heavy concrete buildings, and about half were light industrial steel-frame buildings either at the steel and arms works south of ground zero or at the ordnance and torpedo plant north of ground zero.

Hiroshima and Nagasaki were estimated by Ichikawa and co-workers using thermoluminescence of the crystalline component from roof tiles. Some rather large uncertainties were involved in the distance estimates of their study (Hashizume et al., 1967). Since roof tiles were used only on Japanese houses and all houses close to ground zero were destroyed, the exact location of each roof-tile sample ATE was in doubt. The estimates of gamma-ray and neutron exposure in the JNIRS study by Hashizume et al. (1967) were derived from measurements of the gamma-induced thermoluminescence in decorative-tile and brick samples and of the neutron-induced ^{60}Co radioactivity in steel reinforcing-rod samples taken from commercial buildings that had been repaired and used for a number of years after the bombings. Thus the exact location of each sample ATE was well known, and the uncertainty in the ground distance was minimized. The JNIRS study seemed to confirm the T65D study (Auxier, 1975; Hashizume and Maruyama, 1975a), and the T65D estimates of a survivor's radiation exposure were used, until recently, with a great deal of confidence.

NEUTRON-LEAKAGE DATA

A letter circulated in 1976 by W. E. Preeg of LASL (see appendix to paper by P. P. Whalen, this volume) gave more detail than had been pre-

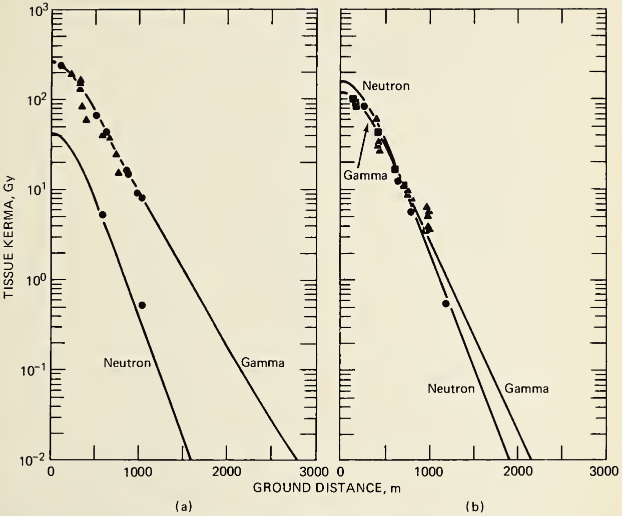

Fig. 5 Comparison of T65D tissue-kerma-vs.-distance relationships with data from Japanese dosimetry studies (Auxier, 1977) for (a) Nagasaki and (b) Hiroshima. Symbols used in (a) are: —, T65D (Auxier et al., 1966). ●, JNIRS (Hashizume et al., 1967). ▲, Kyoto University (Ichikawa, Higashimura, and Sidei, 1966). Symbols used in (b) are: —, T65D (Auxier et al., 1966). For neutrons, ●, JNIRS (Hashizume et al., 1967). For gamma rays, ■, JNIRS (Hashizume et al., 1967) and ▲, Kyoto University (Ichikawa, Higashimura, and Sidei, 1966).

viously available on the leakage spectra of neutrons (and gamma rays) from the Fat Man and Little Boy devices (Tables 2 and 3). The letter includes the results of some additional calculations of neutron penetration in an infinite air medium using the HEART computer code which predicted significantly less neutron exposure in Hiroshima per unit energy yield of Little Boy than the T65D estimates. Such was also the case in more-realistic air-over-ground calculations in 1977 by Kaul and Jarka (1977) who used the ATR4 computer code and by J. Pace (1977) who used the DOT computer code. Some troublesome discrepancies existed in the air-over-ground calculations, however. In 1979 J. Pace (1979) showed that the moisture content of the air was an extremely important parameter in the calculations for Little Boy (see Fig. 6). Kaul and Jarka had used a

TABLE 2

Leakage Spectra of Neutrons from the Little Boy and Fat Man Devices*

	Neutron leakage, neutrons kt^{-1}	
Energy interval, MeV	**Little Boy**	**Fat Man**
6.07×10^{0} to 7.79×10^{0}	9.54×10^{19}	5.34×10^{19}
3.68×10^{0} to 6.07×10^{0}	3.65×10^{20}	1.10×10^{20}
2.865×10^{0} to 3.68×10^{0}	4.39×10^{20}	8.84×10^{19}
2.232×10^{0} to 2.865×10^{0}	7.79×10^{20}	1.51×10^{20}
1.738×10^{0} to 2.232×10^{0}	1.21×10^{21}	1.19×10^{20}
1.353×10^{0} to 1.738×10^{0}	1.54×10^{21}	1.14×10^{20}
8.23×10^{-1} to 1.353×10^{0}	5.18×10^{21}	2.37×10^{20}
5.00×10^{-1} to 8.23×10^{-1}	1.19×10^{22}	1.66×10^{20}
3.03×10^{-1} to 5.00×10^{-1}	1.85×10^{22}	7.91×10^{19}
1.84×10^{-1} to 3.03×10^{-1}	1.65×10^{22}	8.15×10^{19}
6.76×10^{-2} to 1.84×10^{-1}	2.77×10^{22}	9.88×10^{19}
2.48×10^{-2} to 6.76×10^{-2}	1.18×10^{22}	4.98×10^{19}
9.12×10^{-3} to 2.48×10^{-2}	1.81×10^{22}	5.30×10^{19}
3.35×10^{-3} to 9.12×10^{-3}	3.98×10^{21}	6.35×10^{19}
1.235×10^{-3} to 3.35×10^{-3}	3.21×10^{21}	6.83×10^{19}
4.54×10^{-4} to 1.235×10^{-3}	2.11×10^{21}	1.69×10^{22}
1.67×10^{-4} to 4.54×10^{-4}	5.74×10^{20}	6.10×10^{22}
6.14×10^{-5} to 1.67×10^{-4}	1.69×10^{20}	5.30×10^{22}
2.26×10^{-5} to 6.14×10^{-5}	3.76×10^{19}	2.66×10^{22}
8.32×10^{-6} to 2.26×10^{-5}		8.43×10^{21}
3.06×10^{-6} to 8.32×10^{-6}		2.25×10^{21}
1.13×10^{-6} to 3.06×10^{-6}		9.56×10^{20}
4.14×10^{-7} to 1.13×10^{-6}		6.18×10^{19}
Total	1.24×10^{23}	1.71×10^{23}

*As calculated by Preeg (1976).

dry NTS-type of air in their 1977 calculations, whereas J. Pace in his 1977 calculations had used a moist air composition derived from data on atmospheric conditions existing ATE in Hiroshima (Malik, 1976). The best current data on atmospheric conditions ATE in both Hiroshima and Nagasaki are summarized in Table 4 (Malik, 1976; Kaul, 1981; Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki, 1981).

One of the first investigations of this review started in 1979 was of data related to the neutron leakage from Little Boy and Fat Man (Table 5) (Kerr, 1979b). The most recent data came, of course, from the Monte Carlo calculations by Preeg (1976). He used a spherically sym-

TABLE 3

Leakage Spectra of Gamma Rays from the Little Boy and Fat Man Devices*

Energy interval, MeV	Gamma-ray leakage, photons kt^{-1}	
	Little Boy	Fat Man
9.0 to 10.0	1.67×10^{19}	9.52×10^{18}
8.0 to 9.0	1.57×10^{19}	3.66×10^{18}
7.0 to 8.0	5.18×10^{20}	9.52×10^{20}
6.0 to 7.0	1.36×10^{20}	2.56×10^{20}
5.0 to 6.0	1.05×10^{20}	1.82×10^{20}
4.0 to 5.0	2.48×10^{20}	4.46×10^{20}
3.0 to 4.0	3.78×10^{20}	7.03×10^{20}
2.0 to 3.0	5.33×10^{20}	1.94×10^{21}
1.0 to 2.0	7.95×10^{20}	3.65×10^{21}
0.5 to 1.0	1.44×10^{21}	9.80×10^{20}
0.1 to 0.5	6.26×10^{19}	2.00×10^{20}
Total	4.25×10^{21}	9.32×10^{21}

*As calculated by Preeg (1976).

metric mockup of the weapons and a one-dimensional hydrodynamic code which took into account the effect of burnup on neutron (and gamma-ray) leakage from the weapons. Little Boy was cylindrically symmetric, and Preeg knew that the one-dimensional neutron-leakage calculation was approximate, but he thought, in view of the constraints of time and effort, that it would suffice (Marcum, 1978).

The T65D tissue-kerma-vs.-distance relationships in Hiroshima were constructed from neutron-leakage data obtained in the 1964 studies that used the Ichiban critical assembly at LASL (Auxier et al., 1965b, 1966). This was also a spherically symmetric mockup of the Little Boy device. A spherical core of highly enriched uranium was surrounded by spherical reflector and steel shells simulating the weapon's tamper and casing (Thorngate, Johnson, and Perdue, 1966). The spherical design was used to simplify comparisons between experimental measurements and theoretical calculations. However, one LASL calculation which used Monte Carlo techniques gave a value of 0.57 for the number of leakage neutrons per fission and another which used multigroup techniques gave a value of 0.81 (Thorngate, Johnson, and Perdue, 1966). This higher theoretical value was in good agreement with the experimental value obtained by ORNL (Table 5). The ORNL measured value of 0.77 (or more precisely, 0.766) fast neutron per fission and another ORNL measured value of 1.14×10^{-11} Gy [1 Gy (or gray) = 100 rads] for the mean tissue

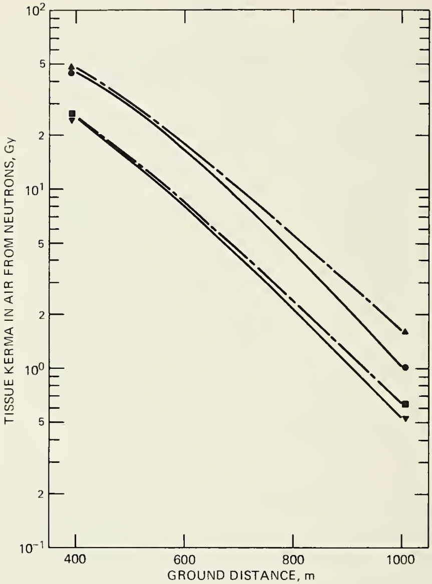

Fig. 6 Effect of moisture content in air on penetration of neutrons from Little Boy at Hiroshima. Air-over-ground calculations: ●——, ATR4 (Kaul and Jarka, 1977). ▼——, discrete ordinate transport with layered moist air (Pace, 1977). Infinite air calculations (Pace, 1979): ▲-——, ANISN with dry air: ρ_{AIR} = 1.13 kg m^{-3}. ■-——, ANISN with moist air: ρ_{AIR} = 1.13 kg m^{-3} and ρ_{WATER} = 0.0176 kg m^{-3}.

kerma per unit fluence (neutrons/cm^2) of fast neutrons having energies greater than 1 keV (Thorngate, Johnson, and Perdue, 1966) gave

$$\frac{1}{4\pi}\left(1.45 \times 10^{23}\ \frac{\text{fissions}}{\text{kt}}\right)\left(0.766\ \frac{\text{neutron}}{\text{fission}}\right)\left(1.14 \times 10^{-11}\ \frac{\text{Gy cm}^2}{\text{neutrons}}\right)$$

$$\left(1 \times 10^{-2}\,\frac{\text{m}}{\text{cm}}\right)^2 = 1.00 \times 10^7\ \frac{\text{Gy m}^2}{\text{kt}} \qquad (1)$$

TABLE 4

Summary of Atmospheric Conditions at Hiroshima and Nagasaki at Time of Explosion

Parameter	Hiroshima	Nagasaki
Atmospheric pressure, mbar		
Ground zero*	1018	1014
Burst height†	950	955
Atmospheric temperature, °C		
Ground zero*	26.7	28.8
Burst height†	23.0	25.6
Relative humidity, %		
Ground zero*	80	71
Burst height†	71	67
Dry-air density, kg m^{-3}		
Ground zero‡	1.151	1.138
Burst height‡	1.095	1.088
Mean	1.123	1.113
Water-vapor density, kg m^{-3}		
Ground zero‡	0.0203	0.0202
Burst height‡	0.0146	0.0160
Mean	0.0174	0.0181
Atmospheric density, kg m^{-3}		
Ground zero‡	1.171	1.158
Burst height‡	1.110	1.104
Mean	1.140	1.131

*Surface weather data from the Hiroshima District Meteorological Observatory at 8:00 a.m. on Aug. 6, 1945, and the Nagasaki Meteorological Observatory at 11:00 a.m. on Aug. 9, 1945. (See, for example, Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki, 1981.)

†Estimates of atmospheric conditions at burst height from Malik (1976).

‡Kaul (1981). Calculations using data on pages F-6 to F-8, D-94, and E-7 to E-12 of the Handbook by Weast (1965).

as the T65D neutron-leakage factor for the tissue kerma at the burst point of Little Boy (Auxier et al., 1966).

Additional neutron-leakage experiments using duplicate Little Boy and Fat Man devices were conducted by ORNL in 1968 at the Burlington Arsenal (Auxier et al., 1969). These experiments were made possible by the increased availability of ^{252}Cf, which produces spontaneous fission neutrons at a rate of about 2.34×10^{12} neutrons sec^{-1} g^{-1} of source material (Barker, 1969). From careful comparisons with neutron sources

TABLE 5

Summary of Data on Total Neutron Leakage and Fast-Neutron Leakage from Several Devices

Device	Type of investigation	Total neutron leakage		Fast-neutron leakage*	
		Neutron per fission	Neutron† per fission neutron born	Neutron per fission	Neutron† per fission neutron born
Ichiban critical assembly	Los Alamos Scientific Laboratory Monte Carlo calculation‡			0.57	0.23
	Oak Ridge National Laboratory experimental measurement‡			0.77	0.31
	Los Alamos Scientific Laboratory multigroup calculation‡	0.81	0.33	0.79	0.32
Little Boy	Oak Ridge National Laboratory experimental measurement§			0.75	0.30
	Los Alamos Scientific Laboratory Monte Carlo calculation¶	0.86	0.35	0.84	0.34
Fat Man	Oak Ridge National Laboratory experimental measurement§			0.003	0.0009
	Los Alamos Scientific Laboratory Monte Carlo calculation¶	1.18	0.41	0.011	0.0036

*Neutrons with energies greater than 1 keV.

†Assumes that the average number of neutrons produced for each fission was 2.5 in the ^{235}U-fueled Ichiban critical assembly or Little Boy device and 2.9 in the ^{239}Pu-fueled Fat Man device.

‡Thorngate, Johnson, and Perdue (1966). §Auxier et al. (1969). ¶Preeg (1976).

calibrated by the U. S. National Bureau of Standards, the neutron emission rate of the nominal 300-μg source used in the measurements was determined as 6.07×10^8 neutrons/sec (Wagner and Shinpaugh, 1968). The Burlington Arsenal replaced the HE and the core components with polyethylene and depleted uranium, respectively, and provided small bores for centering the ^{252}Cf source in the replacement cores of depleted uranium (Fig. 7). A fast-neutron-leakage value based on neutron-flux measurements made at a radius of 2 m from the ^{252}Cf source in the Little Boy device [Fig. 8(a)] is given in Table 6 (Kerr, 1979b). These data indicate a leakage of about 0.30 fast neutron per fission neutron born (or neutron from the ^{252}Cf source) and 0.75 fast neutron per fission if it is assumed that the average number of neutrons produced for each fission was 2.5 in the ^{235}U-fueled Little Boy device (Murray, 1957). If it is further assumed that the average number of neutrons produced for each fission was 2.9 in the ^{239}Pu-fueled Fat Man device, then the 2-m neutron-flux measurements [Fig. 8(b)] indicate a leakage of about 0.0009 fast neutron per fission neutron born (or neutron from the ^{252}Cf source) and 0.003 fast neutron per fission (Kerr, 1979b).

The ORNL experimental data and the LASL theoretical data on neutron leakage from Fat Man differ significantly (Table 5). Because of the high hydrogen content of the thick HE layer about Fat Man's core, most of the fast neutrons were moderated down to thermal energies before they escaped from the device. The thermalized neutrons from the "cold" device used in the ORNL measurements had energies of approximately 0.025 eV, whereas the thermalized "bomb" neutrons from the "hot" device considered in the LASL calculations have energies of the order of 0.1 keV. In fact, the high-energy tail of the Maxwellian distribution (Murray, 1957) of thermalized "bomb" neutrons extended up into the fast-neutron-energy region above 1 keV. Only a small percentage of the neutrons escaped from Fat Man as fast neutrons, but these neutrons were quite energetic because of "hardening" of the fast-neutron spectrum by the hydrogen (Ing and Cross, 1975a) in the thick HE layer. The leakage spectrum of fast neutrons (and bomb thermal neutrons with energies above 1 keV) had an average energy of about 1.6 MeV for Fat Man and only about 0.3 MeV for Little Boy. Mostly fast neutrons escaped from Little Boy, but they were severely degraded in energy because of "softening" of the fast-neutron spectrum by the iron (Ing and Cross, 1975b) in its massive steel casing.

The ORNL experimental data and the LASL theoretical data on both "hot" and "cold" devices seemed to indicate that the effect of weapon burnup on neutron leakage from Little Boy was small (Table 5), and the T65D neutron-leakage factor of 1.00×10^7 Gy m^2 kt^{-1} was found to agree quite well with that obtained from Preeg's 1976 calculations of the

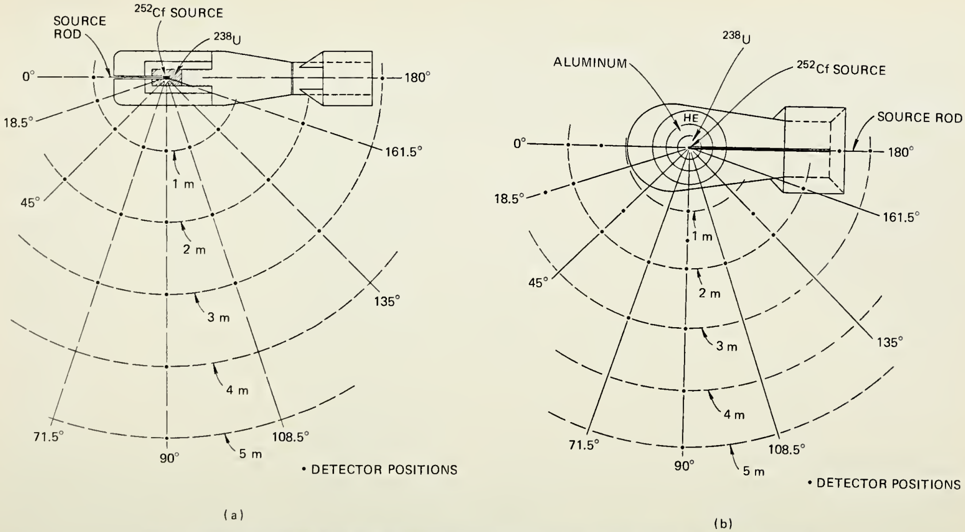

Fig. 7 Detector positions used in Oak Ridge National Laboratory measurements of leakage radiation from (a) Little Boy and (b) Fat Man, looking down from above (Auxier et al., 1969).

TABLE 6

Leakage of Fast Neutrons Based on Oak Ridge National Laboratory Experiments Using a Duplicate Little Boy Device*

Angle of neutron flux measurement (θ), degrees	Angular interval about flux measurement (θ), degrees	Element of area represented by flux measurement (ΔS),† cm^2	Measured neutron flux (Φ), neutrons cm^{-2} sec^{-1}	Neutron leakage rate ($\Phi\Delta S$), neutrons sec^{-1}
0	0 to 9.25	3.27×10^3	153	5.00×10^5
18.5	9.25 to 27.75	2.56×10^4	161	4.12×10^6
45.0	27.75 to 62.25	1.05×10^5	255	2.68×10^7
71.5	62.26 to 80.75	7.66×10^4	356	2.73×10^7
90.0	80.75 to 99.25	8.08×10^4	418	3.38×10^7
108.5	99.25 to 117.75	7.66×10^4	449	3.44×10^7
135.0	117.75 to 152.25	1.05×10^5	466	4.89×10^7
161.5	152.25 to 170.75	2.56×10^4	350	8.96×10^6
180.0	170.75 to 180.0	3.27×10^3	185	6.05×10^5
	Total	5.03×10^5		1.85×10^8

Emission rate of neutrons from ^{252}Cf source = 6.07×10^8 neutrons sec^{-1}

$$\text{Leakage of source neutrons from the weapon} = \frac{\text{Neutron-leakage rate}}{\text{Source emission rate}} = \frac{1.85 \times 10^8}{6.07 \times 10^8}$$

$$= 0.30$$

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*From Auxier et al. (1969).

†Neutron flux measured at a radius of 2 m from ^{252}Cf fission-neutron source located at center of weapon.

neutron-leakage spectrum from Little Boy (Table 7) (Kerr, 1979b). Thus substantial agreement was found among the theoretical and experimental data related to neutron leakage from the Ichiban critical assembly and the Little Boy device, and the investigation failed to resolve the large discrepancy between the older T65D estimates (Auxier et al., 1966) and newer theoretical calculations (Pace, 1977) of the neutron exposure in Hiroshima. Air–ground interface effects (French and Mooney, 1970; Straker, 1971) were also eliminated as a source of this large discrepancy through a series of theoretical and experimental investigations in 1979–1980 that used the U. S. Army Pulsed Radiation Division Reactor (APRDR) (Kazi et al., 1979; Robitaille and Hoffarth, 1980).

SULFUR-ACTIVATION DATA

Several other investigations of this review aimed at resolving the discrepancy between the newer theoretical calculations (J. Pace, 1977)

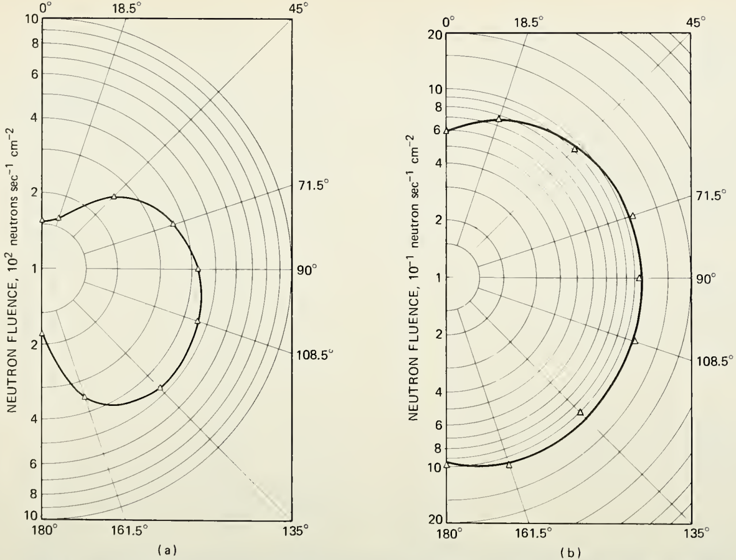

Fig. 8 Neutron flux measured at a radius of 2 m from a ^{252}Cf source at center of (a) Little Boy's core and (b) Fat Man's core. The neutron emission rate of the source was 6.07 × 10^5 neutrons sec^{-1}. (Wagner and Shinpaugh, 1968.)

and T65D estimates (Auxier et al., 1966) of neutron exposure in Hiroshima gave ambiguous results. This was especially true of sulfur activation by fast neutrons, which was more easily related to neutron leakage from the weapons than to thermal neutron activation of phosphorus in bone samples, trace elements in the ground, and cobalt in steel samples (Wilson, 1956; N. Pace and Smith, 1959; Arakawa, 1962; Takeshita, 1975; Hashizume and Maruyama, 1975b). The neutron-leakage calculations by Preeg (1976) and the neutron-transport calculations by J. Pace (1977) for the Fat Man device exploded in Nagasaki were substantiated in 1980 by Kerr (Fig. 9) using data on fluence of fast neutrons with energies above 2.5 MeV as indicated by sulfur-activation measurements made during the Trinity test (N. Pace and Smith, 1959; Klema, 1945) and the Crossroads Able test (Biggers and Waddell, 1957; Glasstone, 1950). However, the newer theoretical calculations by Preeg (1976) and J. Pace (1977) predicted a relative value (Hiroshima/Nagasaki) for sulfur activation of about unity, compared with about 3, quoted by Wilson (1956), and about 3.5, which is obtained if the sulfur activation is assumed to be proportional to the T65D estimates of tissue kerma from neutrons at ground zero in the two cities (Kerr, 1980a).

A major breakthrough in the review came in July 1980 from a report by Miyazaki and Masuda (1953) on Japanese radiation surveys made immediately after the bombings in 1945. This paper states:

> The intensity of radiation (from neutron activation of the ground) about the hypocenter (or ground zero) is approximately 45 J (where 1 J is equivalent to one ion-pair sec^{-1} cm^{-3} of air under standard conditions or a tissue kerma rate of about 17.5 pGy hr^{-1}) both in Nagasaki and Hiroshima (about six months after the bombings). According to K. Kimura the intensity of radiophosphorus caused by slow (or thermal) neutrons in Hiroshima was four times higher in Nagasaki, whereas the intensity of radioactive sulfur caused by fast neutrons at Nagasaki was 1.6 times higher than Hiroshima. Therefore the cause of the intensity of radiation about the hypocenters has not been explained yet.

The relative value (Hiroshima/Nagasaki) of 0.63 for sulfur activation in this report is quite different from the relative value of about 3 quoted by Wilson (1956). An extensive investigation of data related to sulfur activation from the two weapons was therefore undertaken (Kerr, 1980a, 1980b).

The most-detailed and widely referenced set of data on measurements of radioactive ^{32}P produced by the reaction $^{32}S(n,p)^{32}P$ in sulfur used in insulators of utility poles in Hiroshima appears in reports by Yamasaki and Sugimoto (1945, 1953) and by N. Pace and Smith (1946, 1959). (The most accessible is the 1959 ABCC reprint.) All these reports contain data (Table 8) on disintegrations per minute per gram of sulfur (dpm/g S) extrapolated to Aug. 6, 1945, from measurements made on Sept. 20, 1945. These measurements of the beta particles from the decay

TABLE 7

Neutron-Leakage Factor for Tissue Kerma from Neutrons at the Burst Point of Little Boy*

Energy interval, MeV	Energy spectrum of leakage neutrons (ΔN), neutrons kt^{-1}	Normalized energy spectrum of leakage neutrons, $\Delta N^* = \Delta N/N$	Tissue kerma per fluence neutron (K),† Gy $neutrons^{-1}$ cm^2	Mean tissue kerma fluence neutron, ($K\Delta N^*$), Gy $neutrons^{-1}$ cm^2
6.07×10^{0} to 7.79×10^{0}	9.54×10^{19}	7.68×10^{-4}	4.95×10^{-11}	3.80×10^{-14}
3.68×10^{0} to 6.07×10^{0}	3.65×10^{20}	2.94×10^{-3}	4.35×10^{-11}	1.28×10^{-13}
2.865×10^{0} to 3.68×10^{0}	4.39×10^{20}	3.53×10^{-3}	3.96×10^{-11}	1.40×10^{-13}
2.232×10^{0} to 2.865×10^{0}	7.79×10^{20}	6.27×10^{-3}	3.38×10^{-11}	2.12×10^{-13}
1.738×10^{0} to 2.232×10^{0}	1.21×10^{21}	9.74×10^{-3}	3.13×10^{-11}	3.05×10^{-13}
1.353×10^{0} to 1.738×10^{0}	1.54×10^{21}	1.24×10^{-2}	2.80×10^{-11}	3.47×10^{-13}
8.23×10^{-1} to 1.353×10^{0}	5.18×10^{21}	4.17×10^{-2}	2.42×10^{-11}	1.01×10^{12}
5.00×10^{-1} to 8.23×10^{-1}	1.19×10^{22}	9.58×10^{-2}	1.82×10^{-11}	1.74×10^{-12}
3.03×10^{-1} to 5.00×10^{-1}	1.85×10^{22}	1.49×10^{-1}	1.51×10^{-11}	2.25×10^{-12}
1.84×10^{-1} to 3.03×10^{-1}	1.65×10^{22}	1.33×10^{-1}	1.19×10^{-11}	1.58×10^{-12}
6.76×10^{-2} to 1.84×10^{-1}	2.77×10^{22}	2.23×10^{-1}	7.94×10^{-12}	1.77×10^{-12}
2.48×10^{-2} to 6.76×10^{-2}	1.18×10^{22}	9.50×10^{-2}	5.00×10^{-12}	4.75×10^{-13}
9.12×10^{-3} to 2.48×10^{-2}	1.81×10^{22}	1.46×10^{-1}	1.59×10^{-12}	2.32×10^{-13}
3.35×10^{-3} to 9.12×10^{-3}	3.98×10^{21}	3.21×10^{-2}	6.18×10^{-13}	1.98×10^{-14}
1.235×10^{-3} to 3.35×10^{-3}	3.21×10^{21}	2.58×10^{-2}	2.37×10^{-13}	6.13×10^{-15}
4.54×10^{-4} to 1.235×10^{-3}	2.11×10^{21}	1.70×10^{-2}	8.57×10^{-14}	1.46×10^{-15}
1.67×10^{-4} to 4.54×10^{-4}	5.74×10^{20}	4.62×10^{-3}	3.50×10^{-14}	1.62×10^{-16}
6.14×10^{-5} to 1.67×10^{-4}	1.69×10^{20}	1.36×10^{-3}	1.51×10^{-14}	2.05×10^{-17}
2.26×10^{-5} to 6.14×10^{-5}	3.76×10^{19}	3.03×10^{-4}	1.05×10^{-14}	3.18×10^{-18}
Total	1.24×10^{23}	1.00×10^{0}		1.03×10^{-11}

$$\text{Neutron-leakage factor} = (\tfrac{1}{4}\pi)(1.24 \times 10^{23}\ \text{neutrons kt}^{-1})(1.03 \times 10^{-11}\ \text{Gy neutron}^{-1}\ \text{cm}^2)(1\ \text{m}/100\ \text{cm})^2$$

$$= 1.02 \times 10^{7}\ \text{Gy m}^2\ \text{kt}^{-1}$$

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*Based on neutron-leakage-spectrum calculations by Preeg (1976).

†See Appendix B of National Council on Radiation Protection (1971a).

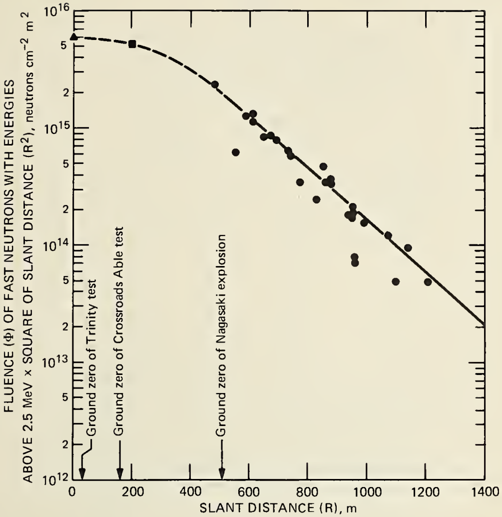

Fig. 9 Comparison of theoretical and experimental data on the fluence of fast neutrons with energies above 2.5 MeV as a function of ln (ΦR^2) vs. R, where Φ is the neutron fluence and R is the slant distance from the burst point of the weapon. ▲, theoretical output value for a Fat Man device (Preeg, 1976). ■, experimental value from Trinity test (Kloma, 1945). ●, experimental values from Crossroads Able test (Biggers and Waddell, 1957). ——, theoretical values for Nagasaki explosion (Pace, 1977).

of ^{32}P were made through a 0.0015-mm aluminum window of a calibrated Lauritsen electrometer at the Institute of Physical and Chemical Research in Tokyo, which had been heavily involved in Japanese research on atomic weapons during the war (Pacific War Research Society, 1972; Coffey, 1971).

No equivalent data from measurements using a calibrated detector could be found for sulfur activation in Nagasaki. The report by Nakaidzumi (1945), which was referenced by Wilson (1956), gives no information on sulfur activation in either city; it provides only estimates of the fast-neutron fluence in Hiroshima derived from the sulfur-activation study of Yamasaki and Sugimoto in late 1945, when the cross section of the $^{32}S(n,p)^{32}P$ reaction was not well known (Yamasaki and Sugimoto, 1953;

TABLE 8

Neutron-Induced ^{32}P Radioactivity in Sulfur (S) of Utility-Pole Insulators in Hiroshima*

Sample†	Ground distance,†‡ m	Initial radioactivity,†‡§ dpm/g S
A	270	2200
B	120	2900
C	350	900
D	380	1100
E	100	2200
F	460	1100
G	440	1300
H	740	660
J	1000	210
K	860	340

*From measurements by Yamasaki and Sugimoto (1945, 1953).

†See map in Yamasaki, Sugimoto, and Kimura (1953) and table in Yamasaki and Sugimoto (1953).

‡See Fig. 7 in N. Pace and Smith (1959).

§Radioactivity in disintegrations per minute per gram of sulfur (dpm/g S) extrapolated to Aug. 6, 1945, from measurements made on Sept. 20, 1945.

Japanese Army Medical School, 1953). If the estimated fast-neutron fluences in Hiroshima by Nakaidzumi (1945) are compared with the estimates in Fig. 2 of the article by Wilson (1956) for the fluence of fast neutrons with energies above 2.5 MeV in Nagasaki (or 3.0 MeV, quoted by Wilson), then the relative values at ground distances between 0 and 500 m (Table 9) indicate about three times as many neutrons above 2.5 MeV in Hiroshima as in Nagasaki.

Some better founded relative values for sulfur activation in the two cities were eventually derived from empirical equations fitted to the measurements by Yamasaki and Sugimoto (N. Pace and Smith, 1959) and the Crossroads Able measurements (Glasstone, 1950) (Table 10). These empirical equations gave relative values (Hiroshima/Nagasaki) that were more consistent with the relative value of 0.63 quoted by Miyazaki and Masuda (1953) and the relative value of about unity derived from the theoretical neutron-leakage data of Preeg (1976) and the theoretical neutron-transport data of J. Pace (1977). The initial sulfur activation was estimated from the reported fast-neutron fluences for the Crossroads Able

TABLE 9

Estimates of the Fluence of Fast Neutrons with Energies Greater than 2.5 MeV in Hiroshima* and in Nagasaki†

Ground distance, m	Fluence of neutrons with energies greater than 2.5 MeV, neutrons cm^{-2}		Hiroshima-to-Nagasaki ratio
	Hiroshima‡	Nagasaki§	
0	8.2×10^{11}	4.0×10^{11}	2.1
500	3.3×10^{11}	7.0×10^{10}	4.7
1000	7.0×10^{10}	6.5×10^{9}	10.8

*From Nakaidzumi (1945).

†From Wilson (1956).

‡See fast-neutron fluences in Table 66, map in Fig. 17-2, and sulfur activation data in Fig. 19 of report by Japanese Army Medical School (1953). These estimates of the fast-neutron fluence in Hiroshima were derived from the sulfur activation measurements of Yamasaki and Sugimoto (1953).

§See Fig. 2 in Wilson (1956). The effective threshold energy for the production of ^{32}P in sulfur by the reaction ^{32}S(n,p)^{32}P is quoted as 3.0 MeV instead of the 2.5 MeV used in this paper.

test (Glasstone, 1950; Biggers and Waddell, 1957) by using a cross section of 230 mb (or 0.23×10^{-24} cm^2) with a probable error of about 30 mb (or ±15%) (Hurst and Ritchie, 1958; Allen et al., 1957; Bainbridge, 1947). In early measurements in which sulfur was used as a threshold detector, the usual practice was to calibrate the counting system by irradiating a sulfur sample with a known fluence of 14-MeV neutrons and to report the activation of other samples in terms of the fluence of 14-MeV neutrons producing equal activation in the sulfur detectors. The value of 230 mb (±15%) agrees quite well with the cross section of about 255 mb for the ^{32}S(n,p)^{32}P reaction at 14 MeV (Allen et al., 1957) and the fission-spectrum-weighted value of 229 mb used for the ^{32}S(n,p)^{32}P reaction in ORNL threshold-detector measurements made during later weapons tests (Hurst and Ritchie, 1958).

Finally, the results of a theoretical investigation of sulfur activation in the two cities, which takes into account the variation in the cross section of the ^{32}S(n,p)^{32}P reaction with neutron energy through the use of theoretical neutron-spectrum data from J. Pace's 1977 calculations, are shown in Figs. 10 and 11. Note that the theoretical values in Fig. 10 for sulfur

TABLE 10

Estimates of Sulfur (S) Activation by Fast Neutrons with Energies Greater than 2.5 MeV in Hiroshima* and in Nagasaki†

Ground distance, m	Initial radioactivity of ^{32}P in sulfur, dpm/g		Hiroshima-to-Nagasaki ratio
	Hiroshima‡	Nagasaki§	
0	2.8×10^3	9.5×10^3	0.29
500	1.0×10^3	1.6×10^3	0.63
1000	1.7×10^2	7.6×10^1	2.2

*From Yamasaki and Sugimoto (1953).

†From Glasstone (1950).

‡See Fig. 7 of N. Pace and Smith (1959). These estimates are based on an empirical equation developed by them to describe the sulfur activation measurements by Yamasaki and Sugimoto (1953).

§See Eq. 7.58.1, Table 7.59, and Fig. 7.59 of Glasstone (1950). These estimates of the fast-neutron fluence are based on sulfur activation measurements made during the Crossroads Able test. The effective threshold energy for the production of ^{32}P in sulfur by the reaction $^{32}S(n,p)^{32}P$ is quoted as 3.0 MeV instead of the 2.5 MeV used in this paper. A mean cross section of 230 mb with a probable error of about 30 mb (±15%) was used in estimating the initial radioactivity of ^{32}P in sulfur from the fast-neutron fluences reported by Glasstone (1950).

activation in Nagasaki are in excellent agreement with the experimental data on the duplicate Fat Man device fired during the Crossroads Able test (Biggers and Waddell, 1957). The low Crossroads Able values probably resulted from inadvertent shielding of some sulfur detectors due to a rather large difference between the targeted and the actual burst points of the air-dropped device. A relative value (Hiroshima/Nagasaki) of about unity for sulfur activation near ground zero is predicted by the theoretical calculations (Figs. 10 and 11). Note, however, that the theoretical data overestimate sulfur activation according to the experimental data from measurements made near ground zero in Hiroshima, but at larger ground distances the experimental and theoretical data are in good agreement. It was eventually determined that this was probably due to the spherically symmetric mockup of Little Boy used by Preeg and to his calculated one-dimensional leakage from the device (Kerr, 1980b). The one-dimensional neutron-leakage approximation becomes less important at the larger ground distances of most interest (i.e., 1000 m or more) since

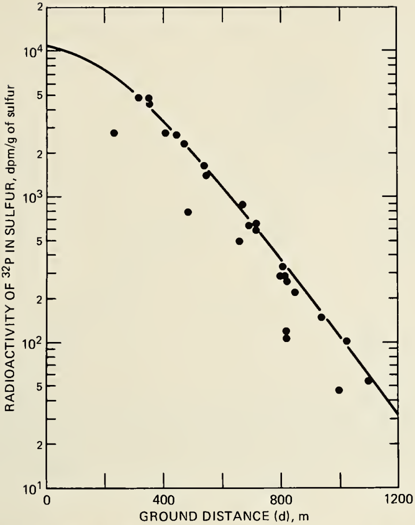

Fig. 10 Comparison of theoretical data on sulfur activation by ^{32}P from the Fat Man device exploded in Nagasaki and experimental data on sulfur activation by the Fat Man device fired during the Crossroads Able test. ●, experimental values from Shot Able of Operation Crossroads (Biggers and Waddell, 1957). ———, theoretical values using Oak Ridge National Laboratory calculations by Pace (1977) and Los Alamos Scientific Laboratory calculations by Preeg (1976).

neutron scattering in air will tend to mask any initial anisotropy in the actual neutron leakage from the cylindrically symmetric Little Boy device.

A blind spot in the neutron leakage through the nose of Little Boy was noted in the experimental measurements in which a duplicate device was used [see 0 and 18.5° angles in part (a) of Fig. 8]. The nose of the device contained considerably more steel than the sides (Birch, 1947; Malik, 1981), and the differences in the leakage spectra of fast neutrons with energies above 2.5 MeV through the sides and nose (Bartine, 1981) were extremely important with regard to sulfur activation near ground zero in Hiroshima. A directional dependence was noted in the experimental data on sulfur activation at ground distances of 500 m or less (Fig. 11). The sulfur activation was lower, in general, to the west than to the east. This would have occurred if the weapon's nose had not been pointed directly

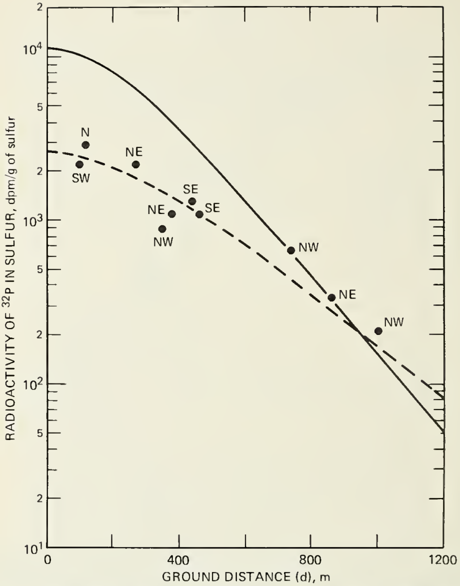

Fig. 11 Comparison of theoretical and experimental data on sulfur activation by ^{32}P from the Little Boy device exploded in Hiroshima. ●, experimental values from measurements by Yamasaki and Sugimoto (1945, 1953). – – –, calculated values using empirical equation by N. Pace and Smith (1946, 1959). ——, theoretical values using Oak Ridge National Laboratory calculations by J. Pace (1977) and Los Alamos Scientific Laboratory calculations by Preeg (1976).

downward ATE. A calculation using drop data from a report by Caudle (1965) indicated that the weapon was canted ATE about 15° with respect to the vertical (Kerr, 1980b). Since the direction of approach of the bombing and observation aircraft was from ENE toward WSW (Fig. 12) (United States Strategic Bombing Survey, 1947; Knebel and Bailey, 1960; Marx, 1967), the weapon's nose would have been pointed at a ground location about 150 m WSW of ground zero. The Fat Man device dropped in Nagasaki (Marx, 1971) was also probably canted ATE at about 15° to the vertical, but it was a spherically symmetric device with nearly isotropic neutron leakage (Fig. 8).

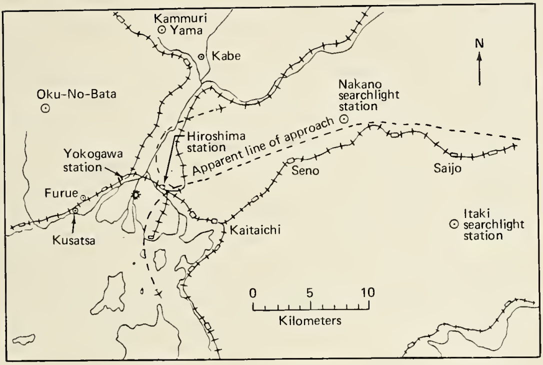

Fig. 12 Map of environs of Hiroshima and direction of approach of the bombing and the observation aircraft (United States Strategic Bombing Survey, 1947). The bombing aircraft turned to the north after releasing Little Boy, and the observation aircraft turned to the south after releasing three parachute-retarded canisters to record the air pressure of the explosion.

STEEL-ACTIVATION DATA

Two steel samples from a steel-reinforced concrete building were used in the JNIRS study by Hashizume et al. (1967). One was a surface steel sample, and one was part of a steel reinforcing rod embedded 8 cm (3 in.) in an exterior wall facing ground zero. The thermal-neutron-induced ^{60}Co radioactivity was measured in the two samples; the results were used to obtain a value for the ^{60}Co radioactivity in the 8-cm-deep embedded sample caused by thermalization of fast neutrons within the concrete wall. To convert this value to a tissue kerma from fast neutrons, Hashizume et al. (1967) used the HPRR neutron-leakage spectrum, which provides a mean tissue kerma of about 2.5×10^{-11} Gy per unit fluence (neutrons/cm^2) of fast neutrons with energies greater than 1 keV. Since the theoretical neutron-transport calculations by Pace (1977) gave a much smaller value, about 1.0×10^{-11}, for this tissue kerma in Hiroshima, the JNIRS estimates of neutron exposure in Hiroshima were predicted to be high by a factor of at least 2.5 (Kerr, 1980a).

Before a more-detailed investigation of the JNIRS steel-activation data was started at ORNL, it was discovered that these data were also being investigated at Lawrence Livermore National Laboratory (LLNL). At an ORNL meeting on Aug. 20, 1980, Loewe and Mendelsohn (1980) of LLNL discussed their studies relating to the dosimetry for atom-bomb survivors. They had attempted to use the LASL neutron-leakage data of Preeg (1976) to calculate the JNIRS measured ^{60}Co-activation value at a ground distance of 1180 m in Hiroshima (Hashizume et al., 1967), but the agreement between the JNIRS measured value and the LLNL calculated value was very poor. The reason for the poor agreement was resolved at the ORNL meeting (Loewe, 1980), and the LLNL calculations eventually provided a revised JNIRS estimate of 0.11 Gy for the tissue kerma from neutrons at a ground distance of 1180 m in Hiroshima compared with the original JNIRS estimate of 0.51 Gy (Loewe and Mendelsohn, 1980). Thus, from the various investigations of data on neutron activation of sulfur and steel, it was concluded that there was significant bias in the T65D estimates of neutron exposure in Hiroshima.

TISSUE KERMA FROM NEUTRONS

Calculations of the weapon radiation fields in air over ground at the large ground distances of interest (i.e., 1000 m or more) demanded the use of a computer code employing discrete ordinate transport (DOT) techniques and a relatively small set of coupled neutron and gamma-ray interaction cross sections (Abbott, 1973). One such set, developed at ORNL at the request of DNA for general use in modern nuclear weapon calculations, consists of 37 neutron and 21 gamma-ray groups (Bartine et al., 1977). It employs a 300°K Maxwellian weighting spectrum for the thermal neutron group and a 1/E weighting spectrum for all higher energy neutron groups. This cross-section set was used by J. Pace in his 1977 calculations for Little Boy and Fat Man. The 1980 calculations by Loewe and Mendelsohn (1980) suggested that the above 37-neutron-group set of cross sections overestimated the neutron exposure for the severely degraded energy spectrum of fast neutrons from Little Boy.

Updated calculations by J. Pace (1981) and Kaul (1981), who used cross-section sets tailored more appropriately to Little Boy and Fat Man, are shown in Fig. 13 (Kerr, 1981). Kaul also used a moist air composition typical of that existing in each of the two cities ATE (Table 4) rather than the dry NTS-type of air of his 1977 calculations. Note that there is only a small difference between the results of the 1977 and 1981 calculations by J. Pace of the neutron exposure in Nagasaki from Fat Man, which had an extremely energetic leakage spectrum of fast neutrons compared with Little Boy. The results of the most recent calculations by LLNL (Loewe and Mendelsohn, 1980), SAI (Kaul, 1981), and ORNL (J. Pace, 1981), in which somewhat different neutron-cross-section data

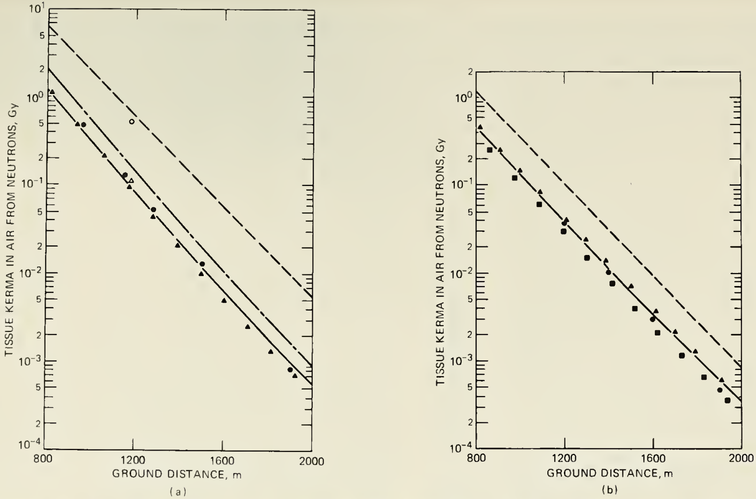

Fig. 13 Comparison of data on neutron exposure in (a) Hiroshima (energy yield, 12.5 kt) and (b) Nagasaki (energy yield, 22 kt) as a function of ground distance. Symbols used in (a) are: ○, JNIRS (Hashizume et al., 1967). △, JNIRS revised (Loewe and Mendelsohn, 1980). ●, Lawrence Livermore National Laboratory (Loewe and Mendelsohn, 1980). ▲, Science Applications, Inc. (Kaul, 1981). — — —, T65D (Auxier et al., 1966) —·—, Old Oak Ridge National Laboratory (Pace, 1977). ——, New Oak Ridge National Laboratory (Pace, 1981). Symbols used in (b) are: ▲, Old Oak Ridge National Laboratory (Pace, 1977). ●, Lawrence Livermore National Laboratory (Loewe and Mendelsohn, 1980). ■, Science Applications, Inc. (Kaul, 1981). — — —, T65D (Auxier et al., 1966). ——, New Oak Ridge National Laboratory (Pace, 1981).

and neutron-energy-group structures but the same DOT calculation techniques were used, are now in close agreement with regard to the neutron exposure in Hiroshima.

The air-over-ground calculations by Pace (1981) used a four-element ground (Pace, Bartine, and Mynatt, 1975) and a layered moist air having an exponentially decreasing density between the ground and the burst height of the weapon (Table 4). Findings by Pace (1979) regarding the importance of moisture content in the atmosphere on neutron penetration are consistent in general with a study by Banks, Klem, and Lichtenstein (1978). In comparison with the effect of atmospheric moisture content on neutron (and secondary gamma-ray) penetration in air over ground, the studies by Banks, Klem, and Lichtenstein (1978) and Gritzner et al. (1976) indicate that composition and moisture content of ground are relatively unimportant. However, it would appear prudent to better characterize both the major and minor constituents of the ground in Hiroshima and Nagasaki (Arakawa, 1962; Hashizume et al., 1969; Hashizume and Maruyama, 1975b).

TISSUE KERMA FROM GAMMA RAYS

The DOT calculations using Preeg's leakage data on both neutrons and gamma rays (Tables 2 and 3) give the radiation exposure to neutrons and gamma rays from the exploding weapon and to secondary gamma rays produced by neutron interactions in the air and ground. To these radiation components must be added the gamma rays emitted by the decay of fission products in the fireball formed after the explosion. Calculation of the latter is quite complex because of the immediate rise of the fireball, the rapid decay of fission products in it, and the blast enhancement of the radiation exposure to these gamma rays. The radiation exposures to delayed neutrons from the fireball and secondary gamma rays produced by delayed neutrons are thought to be negligibly small, but these components need to be investigated further.

An important parameter that has not been taken into account in treatments of the fireball gamma-ray field of a weapon, such as those in the 1977 edition of *The Effects of Nuclear Weapons* (ENW-77) (Glasstone and Dolan, 1977) and *DNA Effects Manual No. 1* (EM-1) (Defense Nuclear Agency, 1972), is the relative source strength of the gamma rays from the fission products of the various fissionable isotopes of uranium and plutonium. Marcum (1978), in a review of data related to dosimetry for atom-bomb survivors, pointed out that gamma rays from the fission products of ^{235}U, ^{239}Pu, and ^{238}U have relative source strengths of about 1.00, 0.67, and 1.75, respectively. In the case of Fat Man, some uncertainties exist in the fraction of the fissions occurring in the ^{239}Pu core and the ^{238}U tamper. It is assumed here that Fat Man had about 80% of its fissions in ^{239}Pu and 20% in ^{238}U and that in the case of Little Boy all fissions occurred in ^{235}U. If ^{235}U is used as a standard, then Fat Man would have a relative source strength of about 0.88 (Marcum, 1978). These source values are reflected in an important way in the total gamma-ray exposure since the fireball gamma-ray component is comparable in magnitude with that from secondary gamma rays.

A study to improve the modeling of the fireball gamma-ray field of a nuclear weapon was undertaken in 1980 by W. H. Scott of Science Applications, Inc. (SAI), and he concluded that comparisons with the best available weapons-test measurements were improved when the correct time-dependent decay spectra of gamma rays from the fission products of uranium and plutonium were included in the calculations (Scott, 1981). The agreement between measured and calculated values was within 10 to 20% when the appropriate isotopic time-dependent sources for a tested weapon were incorporated in the NUIDEA code of SAI (Straker and Huszar, 1976), which uses the so-called LAMB blast enhancement and fireball-rise models (Needham and Wittwer, 1975). One important finding of Scott's 1980 study was that the data in EM-1 and ENW-77 overestimate radiation exposure from the fireball gamma-ray field of Little Boy and Fat Man by factors of 2 or more.

The results of the best state-of-the-art calculations by Scott (1981) and J. Pace (1981) have been summed to obtain the gamma-ray exposure values for Hiroshima and Nagasaki (Fig. 14) (Kerr, 1981). Energy yields and burst heights of 22 kt and 503 m, respectively, were used for the Nagasaki explosion and 12.5 kt and 580 m, respectively, for the Hiroshima explosion. Note that the calculated values and experimental JNIRS values, which for reasons discussed earlier are usually considered to be the more reliable of the two Japanese data sets, agree to within 10% for Hiroshima. The overall agreement is not as good for Nagasaki, where the difference is about 20% at a ground distance of about 1000 m. Sensitivity studies, which are needed to set limits of precision on the calculated values for both neutrons and gamma rays, may help to resolve the reasons for the larger observed difference for Nagasaki.

KERMA RELAXATION LENGTH

Results of the recent calculations by J. Pace (1981) and Scott (1981) are compared with the T65D tissue-kerma-vs.-distance relationships of Auxier et al. (1966) and the experimental gamma-ray measurements from the Crossroads Able test of EAW-50 (Glasstone, 1950) in Fig. 15 as functions of ln (KR^2), where K is the tissue kerma in air and R is the slant

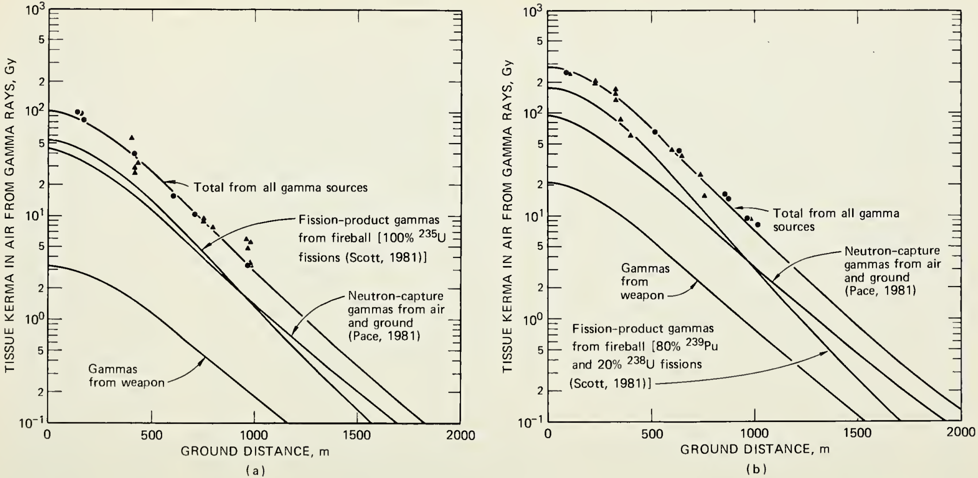

Fig. 14 Comparison of theoretical and experimental data on gamma-ray exposure in (a) Hiroshima (burst height, 580 m; energy yield, 12.5 kt) and (b) Nagasaki (burst height, 503 m; energy yield, 22 kt) as a function of ground distance. ▲, Kyoto University (Ichikawa, Higashimura, and Sidei, 1965). ●, JNIRS (Hashizume et al., 1967). ——, Oak Ridge National Laboratory/Science Applications, Inc. (this work).

distance from the burst point of the weapon (Fig. 3). If the plot of ln (KR^2) vs. R is a straight line, then the radiation exposure can be specified by the relationship

$$K = G_o \frac{\exp(-R/L)}{R^2} \tag{2}$$

where G_0 is the extrapolated source term (i.e., ordinate intercept) and L is the kerma relaxation length (i.e., slope of the straight line). This equation was assumed in the T65D study (Auxier et al., 1966) and in several previous studies of dosimetry for the Japanese atom-bomb survivors (York, 1957; Wilson, 1956; Harris, 1955) (Table 11).

The calculations by J. Pace (1981) yielded essentially the same kerma relaxation length for neutrons in Nagasaki as that assumed in the T65D study for neutrons in both cities [Fig. 15(a)]. During the Operation BREN studies with the HPRR (Stephens and Aceto, 1962) and a variety of modern weapons tests (Auxier, Cheka, and Sanders, 1961; Hurst and Ritchie, 1958; Harris et al., 1955), an invariant or equilibrium spectrum of air-transport neutrons was observed starting at a distance R of several hundred meters, and the kerma relaxation length for neutrons was found to be a constant at greater distances (Glasstone, 1957, 1962). This simply did not happen in Hiroshima because of the severely degraded energy spectrum of fast neutrons from Little Boy [Fig. 15(a)]. The distance R from the burst point was nearly 2000 m before the spectrum of air-transported neutrons reached an equilibrium state and the kerma relaxation length approached a constant value (J. Pace, 1981). At smaller distances R, the kerma relaxation length, varied in magnitude, and the above equation was not applicable.

A constant kerma relaxation length for gamma rays in Hiroshima was also assumed in the T65D study by Auxier et al. (1966) [Fig. 15(a)] on the basis of data from (1) the Operation BREN studies using the HPRR and a ^{60}Co source to simulate the secondary and fireball gamma-ray fields of a weapon, respectively (Haywood, 1965), and (2) total gamma-ray field measurements made during several of the most nearly appropriate tests of modern fission weapons (i.e., nominal energy-yield weapons fired at about the same burst height as Little Boy) (Auxier, Cheka, and Sanders, 1961). The HPRR or a modern fission weapon (i.e., a gun-assembly device with no HE, like Little Boy, or an implosion-type device with a thin HE system) produces very few thermalized neutrons compared with a Fat Man device with a thick HE system (Marcum, 1978). For Fat Man, the copious number of "bomb" thermal neutrons (Table 5) interact with nitrogen in the HE of the weapon and in the surrounding air to produce an intense "localized" source of high-energy gamma rays (3 to 10 MeV). The secondary gamma rays are produced throughout a larger volume of air for

TABLE 11

Summary of Parameters from Four Studies of Dosimetry for the Atom-Bomb Survivors*

Parameter	Auxier et al. (1965)	York (1957)	Harris (1955)	Wilson (1956)†
Hiroshima				
Energy yield (W), kt	12.5	18.5	18.5	20
Height of burst (H), m	570	550	610	600
Kerma relaxation length (L), m				
Neutrons	198‡	218	201	196
Gamma rays	250‡	346	329	320
Extrapolated source term (G_0),§ Gy m^2				
Neutrons	8.70×10^8	8.64×10^8	1.12×10^9	7.66×10^9
Gamma rays	3.45×10^8	2.16×10^8	2.64×10^8	3.34×10^8
Nagasaki				
Energy yield (W), kt	22	23	23	20
Height of burst (H), m	500	520	520	600
Kerma relaxation length (L), m				
Neutrons	198‡	218	201	196
Gamma rays	350‡	346	329	320
Extrapolated source term (G_0),§ Gy m^2				
Neutrons	1.30×10^8	1.25×10^8	1.64×10^8	5.65×10^8
Gamma rays	2.75×10^8	2.68×10^8	3.29×10^8	3.34×10^8

*From Auxier et al. (1965), York (1957), Wilson (1956), and Harris (1955).

†Values of the extrapolated source term for neutrons are taken from Table 1 of Auxier et al. (1966). Dates in column heads are dates of original study, not publication dates.

‡Normalized by Auxier et al. (1966) to an estimated atmospheric density of 1.13 kg m^{-3} in both cities at time of explosion.

§One gray unit (1 Gy) is numerically equal to 100 rad units and to approximately 95 R (or rep units) used in some earlier reports.

the HPRR, a modern fission weapon, or for Little Boy. As pointed out by Auxier et al. (1966), the kerma relaxation length should be smaller in Hiroshima than in Nagasaki on the basis of geometry alone. This appears to be the situation at smaller distances in Hiroshima, but at greater distances the secondary gamma rays produced by the severely degraded energy spectrum of fast neutrons from Little Boy start to behave as a localized source (or point source) and the kerma relaxation length starts to resemble that of Fat Man in Nagasaki [Fig. 15(b)].

Finally, comparisons of the newer calculations of the gamma-ray exposure in Nagasaki have shown closer agreement with data from the Crossroads Able test (Glasstone, 1950) than with the T65D estimates (Auxier et al., 1966) [Fig. 15(b)]. The T65D tissue-kerma-vs.-distance

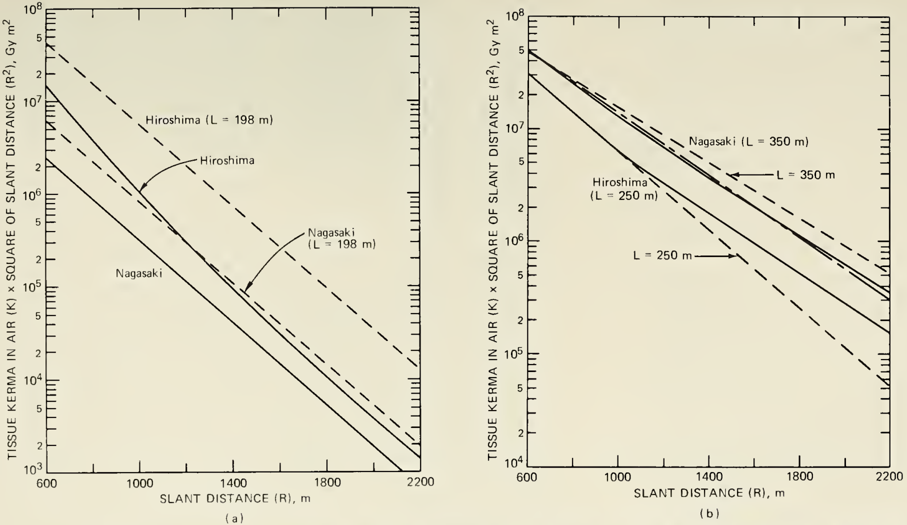

Fig. 15 Comparison of best state-of-the-art calculations and T65D estimates of (a) the neutron and (b) the gamma-ray exposure in Hiroshima and Nagasaki as a function of ln (KR^2) vs. R, where K is the tissue kerma in air and R is the slant distance from the burst point of the weapon. Symbols used in (a) are: ——, new values (Pace, 1981). — — —, T65D estimates (Auxier et al., 1966). Symbols used in (b) are: — ———, EAW-50 (Glasstone, 1950). — — —, T65D estimates (Auxier et al., 1966). ——, new values [Pace (1981) and Scott (1981)].

relationship for gamma rays in Nagasaki was constructed from LASL film measurements made during the Ranger Fox test of a Fat Man implosion-type device in 1952 (Auxier, 1977; Storm, 1952). Simultaneous film measurements made during later weapons tests by both the Evans Signal Depot and by LASL (Nuclear Development Corporation of America, 1957; Storm and Bemis, 1955) and laboratory studies by LASL (Storm and Bemis, 1955) indicated that their film measurements overestimated the gamma-ray exposure, with the degree of overestimation varying with distance. This is a moot issue since the T65D values came from the test firing of a modified Fat Man implosion-type device with a tamper and core quite different from those in the Nagasaki weapon (Marcum, 1978; Malik, 1954), and it cannot be assumed, on the basis of present knowledge, that either the neutron or gamma-ray output of these two devices was the same.

DISCUSSION

Some findings of the review are that the neutron exposure levels in Hiroshima were probably less than the T65D estimates by factors varying from about 4 at a ground distance of 1000 m to 8 at 2000 m (Fig. 16), and the gamma-ray exposures were greater than the T65D estimates starting at a ground distance of about 1000 m and were probably larger by a factor of about 3 at 2000 m [Fig. 16(a)]. In Nagasaki the situation was reversed with respect to gamma rays, and the T65D estimates were higher (Fig. 16), but the differences were small (i.e., about 20% at a ground distance of 1000 m and 30% at 2000 m). As a result, it now appears that leukemia and other late effects at lower exposure levels in Hiroshima were due largely to gamma rays rather than to neutrons. This may not be true at higher exposure levels in Hiroshima, however.

If the newer radiation-exposure values shown in Fig. 16 are used (Kerr, 1981), then the correlation between leukemia in survivors of the two cities and absorbed dose to active marrow of the survivors is not as good as that obtained by Loewe and Mendelsohn (1980). They attribute the leukemia at all exposure levels in the two cities to gamma rays. However, survival inside houses in Hiroshima started at about 700 m and reached 50% at about 900 m (Davis, Baker, and Summers, 1966). At these, and even slightly larger, ground distances in Hiroshima, the neutron exposures inside houses were not negligible compared with the gamma-ray exposure if the relative biological effectiveness of neutrons for whole-body exposure is of the order of 10 (National Council on Radiation Protection, 1971a, 1971b). The results of any reanalysis of data on observed biological effects in the survivors should be regarded as highly speculative until some of the following issues have been investigated in more detail.

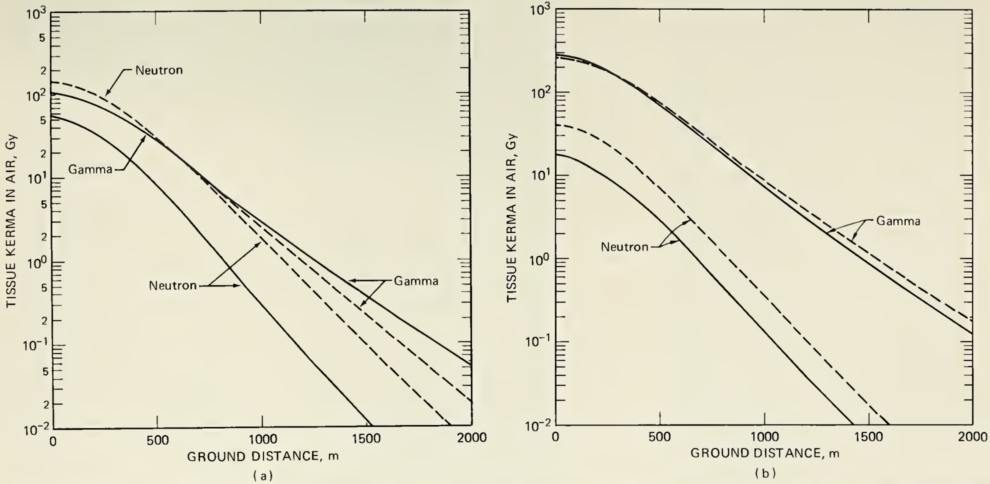

Fig. 16 Comparison of values from best state-of-the-art calculations and T65D estimates of the radiation exposure in (a) Hiroshima (energy yield, 12.5 kt) and (b) Nagasaki (energy yield, 22 kt). — — —, T65D values (Auxier et al., 1966). ——, new values [Pace (1981) and Scott (1981)].

Organ-Dose Factors

The T65D estimates take into account a survivor's distance from ground zero and shielding by surrounding structures, but they do not consider the shielding of an organ of interest by overlying tissue of a survivor's body. Factors from studies by Jones (1977) and by Kerr (1979a) for converting the T65D estimates into an absorbed dose in an organ of a survivor must be updated by using data from newer theoretical calculations of the energy and angular distributions of the neutron and gamma-ray fields in the open and inside a Japanese house. New techniques developed at ORNL for inserting mathematical models of the body into the MORSE radiation-transport code (Emmett, 1975) appear to provide the best calculational approach. Recent improvements in the mathematical models of the body (Cristy, 1980, 1981) and in the response function for the absorbed dose to active marrow (Kerr, 1980c) should also be used in updating the organ-dose factors.

Shielding Factors for Houses

The radiation exposure to survivors inside houses ATE has been estimated by using the nine-parameter formulas developed by Cheka et al. (1965). An investigation of a large number of actual house-shielding cases (see, for example, Fig. 4) by Milton and Shohoji (1968) indicated that typical shielding factors (or transmission factors) for gamma rays and neutrons were about 0.90 and 0.31, respectively, for Hiroshima and about 0.81 and 0.34, respectively, for Nagasaki. Marcum (1981) recently suggested that the house-shielding factors for gamma rays were probably more like 0.55 in Hiroshima and 0.50 in Nagasaki. Adjoint MORSE calculations, which have been used in other shielding studies (Rhoades, 1974; Scott, Faverty, and Dietz, 1975), are needed to update the shielding factors for typical Japanese houses (Noble, 1968; United States Strategic Bombing Survey, 1947).

Energy Yield of Little Boy

The energy yield used in the T65D study by Auxier et al. (1966) was 12.5 kt, and the probable error was later estimated to be about 1 kt (Auxier, 1975). Malik (1980) recently suggested that the energy yield of Little Boy was 15 (±3) kt. A probable error greater than 1 kt in the T65D value is indicated by Malik's review of data on distances for equal physical damage in the two cities (Auxier, 1977; Auxier et al., 1968) and data on the air-pressure record from parachute-retarded canisters dropped by the observation aircraft (Auxier, 1977; Auxier et al., 1968; Caudle, 1965), but his findings do not appear sufficient at present to warrant a change to

15 kt, since several other studies predict an energy yield more like the T65D value of 12.5 kt (Penney, Samuels, and Scorgie, 1970; Davis et al., 1963; Kimura, Akutsu, and Tagima, 1953). It appears necessary to collect and review all data related to the energy yield of the Little Boy device dropped in Hiroshima.

Neutron Leakage from Little Boy

The gun-assembly device was cylindrically symmetric, and Preeg (1976) knew that the one-dimensional calculation was approximate, but he thought, in view of time and effort constraints, that it would suffice (Marcum, 1978). However, a cylindrically symmetric mockup of Little Boy and a two-dimensional calculation are apparently needed to establish the neutron exposure and neutron activation in Hiroshima more precisely.

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DISCUSSION

Jablon: You stated that Marcum has estimated that the attenuation provided by housing in Hiroshima for gamma rays is much greater than what has been used. I haven't heard any explanation of that, and I thought that factor had been measured at the Nevada Test Site. Would you comment on that?

Kerr: Marcum pointed out in his report that the tissue kerma from neutrons and gamma rays at the point of the Nevada Test Site measurements was essentially the same. As a result, a lot of secondary gamma rays were produced in the walls of the house. The actual data show gamma-ray exposures inside houses from the neutron and gamma-ray fields that are sometimes higher than the gamma-ray exposure in the open. This was probably due to the secondary gamma rays.

Jablon: So the dose is determined not only by the attenuation of incoming gammas by the housing but also by the whole complex working together?

Kerr: Right. That's the main problem here.

Rossi: We know from a great amount of radiobiological information that the biological effect of neutrons is a function not only of the dose but also of the energy. The question is whether the neutron energy spectrum inside the houses was the same as outside. If not, this may be a substantial source of error, and any future calculations should definitely take into account not only the neutron dose reaching the exposed people but also its energy spectrum. I think this may turn out to be an important factor.

Kerr: The neutron and gamma-ray spectra inside houses will be available from the house-shielding calculations by Scott, Woolson, Pace, and others.

Loewe: You compared the Livermore neutron doses with yours and found, I think, good agreement. How would you characterize a comparison between the Livermore gamma doses and those you are quoting now?

Kerr: The neutron doses compared here were from your preliminary report D-80-14. There are some significant differences between the gamma-ray doses given in that report and the ones I presented here. However, our gamma-ray doses and the ones you presented here appear to be in reasonably good agreement if allowance is made for the difference between the 12.5-kt yield which I used for the Hiroshima weapon and the 15-kt yield which you are using for that weapon.

Dennis: I agree with Rossi that we should know the neutron spectrum reaching the people inside the houses; in addition, we should also know something about the gamma spectrum reaching the people in the houses because different energies of gamma radiation may differ in their biological effectiveness and would certainly differ in their penetration to the organs.

Kerr: The question today is what needs to be done and what is worth doing. What you suggest can be done, but it takes money. The bottom line is that we get to do what we have funding to do.

Wyckoff: You multiplied RBE by absorbed dose and got dose equivalent in sieverts (Sv), and that is not the proper formulation—one must use quality factor rather than RBE. The next point is much more important. You were comparing the risks in terms of being proportional to those products, and I think that is not legitimate unless the products for both neutrons and gamma rays are proportional to (i.e., linear with) the risk.

Kerr: A lot of the earlier studies of effects among the A-bomb survivors were based on only the tissue kerma in air. What I gave was just an example, not anything rigorous. I think there still could be some neutron effects in close.

Wyckoff: You want to be careful when you say the RBE was 10 because that means you are assuming you can compare the possible risks due to neutrons and to gamma rays in terms of the ratio of the products of the absorbed dose and the RBE. I think that cannot be so unless both of the risk curves are linear.

Radford: Since the leukemia data have been stressed so far in this presentation, I would like to point out that, if one wants to make comparisons between the two cities, for leukemia the mortality data for Nagasaki are so inadequate as to make fruitless any attempt at quantitative estimates of either the shape of the dose–response curve or the RBE calculated at low doses. Up to 1974, there were only 22 leukemia deaths in the Nagasaki group exposed to more than 10 rads kerma, according to the T65 doses. Dividing those 22 cases into eight dose categories gives an indeterminate dose–response relationship, as I think can be shown statistically by setting up models and calculating the uncertainty in any particular dose point. The Nagasaki data have now been carried up to 1978, and they clearly show that the excess risk has disappeared, so that those 22 deaths, minus the expected ones, are all the excess leukemia deaths that will ever be seen in Nagasaki. Therefore I think it is time to look at some other biological end points, which will come up at this meeting, in determining what a comparison of the empirical evidence in the two cities reveals about the relative effects of the two bombs.

Levin: I realize RBE played a small part in your talk, but many of us are concerned about it. If indeed most of the cases were at 1000 m or beyond and if indeed virtually no neutrons are present beyond 1000 m, then isn't it ludicrous to talk about an RBE?

Kerr: I made one simple point, that there could still be neutron effects. And be careful what you do until you have better data to base your analysis on—I obviously didn't have good enough data, because everyone has found fault with it.

Sinclair: Your point is well taken because you could put in a larger RBE and have a significant component due to neutron dose. That question should be held until later because we are still dealing with the physical factors. Dr. Jablon had a question about Marcum's suggestion to change the shielding factor for gamma rays from about 0.9 to 0.5. (That is a big change.) You replied that complications arose from the generation of gamma rays in the walls due to neutrons. That doesn't explain the *lowering* of the shielding factors. What reason does Marcum give?

Kerr: I thought we said before that the neutron-to-gamma dose ratio in Hiroshima and Nagasaki was so different from that in the fields where the Nevada Test Site measurements were made that secondary gamma-ray production did not occur to the same extent in the houses in Japan.

Sinclair: Do you mean that so many of the gamma rays previously estimated to be inside the houses were due to the neutrons that lowering the neutron dose took away a very large component?

Kerr: That accounts for a significant part of the change.

Sinclair: I didn't realize that effect was so large.

Kaul: How were house-shielding factors originally applied with respect to range?

Kerr: I think they had shielding histories compiled on everyone within 1600 m in Hiroshima and 2000 m in Nagasaki—that is, for all the people in the ABCC records or RERF studies. Beyond those distances there are shielding histories on some people but not all.

Yields of the Hiroshima and Nagasaki Explosions

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ABSTRACT

Estimates of the yields of the Hiroshima and Nagasaki explosions remain rather uncertain. The Fat Man device that exploded over Nagasaki had been tested at Project Trinity and was the explosive for the Operation Crossroads tests. Its yield has been reasonably well established by radiochemical and fireball data, together with calculations, as 22 ± 2 kt. The explosion of the Little Boy device over Hiroshima, however, was the only detonation of this device. Blast effects observed at Hiroshima compared with similar effects at Nagasaki suggest a yield of 12 ± 4 kt, which is based on the Nagasaki yield of 22 kt. A comparison of the similar thermal effects at the two cities suggests a yield of 15 ± 3 kt; old calculations support this value. A reevaluation of the pressure data obtained by gauges in canisters dropped from an accompanying aircraft suggests a yield of 17 ± 4 kt.

Pending the results of further studies, the suggested yields of the two explosions are:

Nagasaki	22 ± 2 kt
Hiroshima	
Surface blast	12 ± 4 kt
In free air	15 ± 3 kt

Ongoing experimental and theoretical work should improve the Little Boy yield estimate. The current suggested best value for the Hiroshima yield is 15 kt.

Estimates of the explosion yields of the weapons used against Hiroshima and Nagasaki, together with the nuclear outputs, even after 36 years remain uncertain by large factors. Many explanations could be offered but are irrelevant.

The Little Boy exploded over Hiroshima was a gun-type device using enriched uranium; this was the only detonation of this kind of device. The Fat Man exploded over Nagasaki was an implosion device using plutonium; it was also tested at Trinity in New Mexico and was the explosive for the Operation Crossroads tests (Able and Baker) at Bikini Atoll in 1946. Consequently some test data are available from Fat Man.

The plans were to use two different methods to measure the yields of the combat drops with instrumentation on or dropped from accompanying aircraft. One aircraft was equipped with a Fastax camera to obtain photographs of the early fireball expansion as a function of time; this technique had been tested at the Trinity test with excellent results. Fireball records obtained by B. Waldman with this camera on the Hiroshima drop were destroyed by malfunction of the film-processing equipment. R. Serber was to have operated the camera on the Nagasaki mission, but the instrumentation aircraft not only took off without him but also did not rendezvous with the strike aircraft; therefore no fireball records were obtained. Despite the very successful measurement of the fireball yield on the Trinity test, no such data were obtained on either combat drop. Crossroads Able, an airdrop of a Fat Man over naval targets, could have supplied further fireball records for that device, but the large miss distance put the detonation outside the field of view of all but one camera—a streak camera that provided marginal data.

The other planned method of yield measurement was to determine the blast overpressure by using gauges dropped from an accompanying aircraft with the data telemetered to that aircraft. Plans had been made to test this technique also on Trinity, but bad weather precluded the aircraft from being on station; however, ground-based measurements were made. The method was tested on the 100-ton high-explosive test prior to Trinity with good results and on the Crossroads tests with poor results. It yielded data from both Hiroshima and Nagasaki drops—one record out of a possible three for each of the two missions, although the record for Nagasaki was off scale. The measurements were made by a team headed by L. W. Alvarez (1963).

Yield estimates can be made in several ways, such as

Calculation
Radiochemistry
Fireball radius vs. time
Thermal radiation
Blast
  Overpressure vs. time
  Effects upon objects
    (integrated overpressure)
Neutrons and gamma rays

Calculations with modern design codes can produce reliable estimates. The effort required and the accuracy are somewhat design dependent. For Fat Man, calculations give 22 ± 2 kt with high confidence. Modern calculations for Little Boy are more difficult and are under way. Older estimates have ranged from 15 to 25 kt, with the low estimates being more credible. By the nature of the device, the estimates have considerable uncertainty.

Radiochemical analysis of the debris of a nuclear explosion is the standard technique for yield determination. There were no debris samples for

Little Boy. For Fat Man, cloud sampling yielded data from Trinity and both Crossroads tests, Able and Baker. C. I. Browne, who reevaluated those data by modern analysis methods, recommends a best value for Fat Man of 21 ± 1.5 kt.

Data for fireball radius vs. time for Fat Man from the Trinity and Crossroads Able tests are also available. The Trinity data are very good, whereas the Able data are poor. Reevaluation of those data by D. Eilers gives a value for Trinity of 22 ± 2 kt and a value for Able of 21 ± 3 kt. The current official yield for Fat Man listed in the Nevada Operations Office (1981) summary of announced events is 23 ± 3 kt, which is based on an earlier evaluation of the fireball data and recommended by W. Ogle. A probably better value is 22 ± 2 kt, which is based on the more modern radiochemical and fireball analyses of the data as well as on the calculations. The "hard" yield data for Fat Man are summarized as follows:

	Yield, kt
Radiochemistry	
Trinity test	20.3
Crossroads Able test	20.4
Crossroads Baker test	21.7
Recommended	21 ± 1.5
Fireball	
Trinity test	22.2
Crossroads Able test	21.1
Recommended	22 ± 2

Assuming the yield of the Nagasaki explosion to be known, the yield of the Hiroshima explosion can be estimated by equating similar effects in the two cities. By using observations of similar thermal effects, I calculated the estimates shown in Table 1. I have equated effects at the observed distances (by assuming the thermal flux to be proportional to yield) to the inverse square of distance with values of atmospheric transmission from Glasstone and Dolan (1977). My source of data is Auxier (1977). A breakdown of the data set is given in Table 2. The atmospheric transmission was assumed to be the same for the two cities, i.e., a 12-mile visibility. This method gives an estimate of 15 ± 3 kt, with no correction for nonorthogonal incidence. (Assuming that thermal effect varies as the cosine of the angle of incidence, the Hiroshima yield estimate is 17 ± 4 kt.) Observation of thermal effect is perhaps the most useful method for determining the Little Boy yield.

Like the observations of similar effects from thermal radiation, observations of similar blast effects permit estimation of the Hiroshima yield if

TABLE 1

Thermal Effects Based on Equal Effects at Hiroshima and Nagasaki

References	Estimated Little Boy yield,* kt
Auxier (1977)	12.7 ± 1
Malik (1976; 1980)	15.1 ± 3
Kerr (1980, 1981)	13.6 ± 3.5
	12.4 ± 3.5

*Based on Fat Man yield of 22 kt.

Note: After correction for angle of incidence, yield was ~17 kt.

TABLE 2

Data Base for Thermal Effects Estimate*

[Ratio = 0.685 ± 0.144; yield = 15.1 ± 3.2 kt]

Effect	Distance from epicenter, ft		Yield ratio
	Hiroshima	Nagasaki	
Roughening of polished granite			
British estimate	1,500	2,000	0.870
Japanese estimate	2,000	3,000	0.640
USSBS† estimate	1,300		
Nagaoka estimate (Auxier, 1977)	3,450	5,250	0.494
Flash burns on wood			
British estimate	9,000	10,000	0.806
Penney, Samuels, and Scorgie (1970) estimate	9,500	11,000	0.734
USSBS† estimate	13,000	9,200	2.160‡
Flash burns on roof tile			
Nagaoka estimate (Auxier, 1977)	1,970	3,200	0.567

*The Hiroshima yield estimate is based on a Nagasaki explosion yield of 22 kt.

†U. S. Strategic Bomb Survey (1947).

‡Excluded from average.

the yield of the Nagasaki explosion is assumed to be known. Since the blast overpressure vs. range from ground zero for explosions over ideal surfaces is also a strong function of the height of burst (HOB) of the explosion, the comparison of blast effects is more complicated than that of thermal effects. Neither absolute nor scaled heights of burst were equal for the two explosions. To correct for both range and height-of-burst variations, I used an empirical fit to the height-of-burst curves valid for the overpressure range of 1 to 6 psi and scaled heights of burst of 500 to 900 $ft/kt^{1/3}$, which encompass the data for the two explosions. The results are shown in Table 3. I have used a better interpolation formula for this estimate than for my earlier estimate; the present relation is more reasonable. This is given together with a breakdown of the data used for my estimates in Table 4, where again the data base is taken from Auxier's *Ichiban* (1977) plus one data point from Penney, Samuels, and Scorgie (1970), which may be the best data point. In the evaluation ideal surfaces or at least similar surfaces in the two cities are assumed. The built-up areas, however, may not be describable as ideal surfaces; also the cities and ground terrain were not very similar. The estimate derived is likely a lower limit. Uncertainties are also introduced in the evaluation of the equivalent range of similar effects. Because yield varies as the cube of the distance, the uncertainty in yield is three times the uncertainty in range.

TABLE 3

Blast Effects Based on Similar Effects at Hiroshima and Nagasaki

References	Estimated Little Boy yield,* kt
Auxier (1977)	12.5 ± 1
Malik (1976)	14.2 ± 2
Malik (1980)	12.2 ± 2
Kerr (1980, 1981)	12.2 ± 3

*Based on Fat Man yield of 22 kt.

The evaluation of blast effects on an absolute basis was also reported by Penney, Samuels, and Scorgie in 1970. They estimated the yields as 12 ± 1 kt for Hiroshima and 22 ± 2 kt for Nagasaki. Some of us have reservations about their interpretation, and their report is being reviewed by blast experts in the United States.

The evaluation of the overpressure-vs.-time data obtained by the Alvarez team from pressure gauges in the canisters dropped by parachute from the instrumentation aircraft *Great Artiste*, which flew in formation with the strike aircraft *Enola Gay*, may be the second-best method for estimating the yield of the Hiroshima explosion, but it has been complicated by the incomplete and inconsistent records of the missions.

TABLE 4

Hiroshima Yield from Equivalent Blast Effects

	Distance from ground zero, ft		Hiroshima*	
Effect	Hiroshima	Nagasaki	Overpressure (P), psi	Yield (W_H), kt
Data base from Auxier (1977)				
Collapse of typical houses	6750	7450	3.17	12.6
Structural damage	7900	8600	2.54	13.2
Serious nonstructural damage	7900	9000	2.36	10.9
Data point from Penney, Samuels, and Scorgie (1970)				
10 to 20% of empty 4-gal petrol cans undamaged	5700	6400	4.02	12.0
				12.2 ± 1.2

*Weapon yield for Nagasaki (W_N) is assumed to be 22 kt.

Note: Assuming nonideal surfaces, yield for Hiroshima is 17 kt.

Interpolation with formula:

$$P = 18.3 \left(\frac{\text{HOB}}{W^{1/3}}\right)^{0.32} \left(\frac{D}{W^{1/3}}\right)^{-1.56\left(\frac{\text{HOB}}{W^{1/3}}\right)^{-0.062}} \text{psi}$$

Some of the yield estimates derived from those data are given in Table 5. The differences in these values are due both to the method used and to the use of different values of the parameters, which are, primarily, distance determined from aircraft altitude and speed together with bomb

TABLE 5

Overpressure vs. Time (Hiroshima Record)*

Reference	Estimated Little Boy yield, kt
Penney (1946)	17.4
Hirschfelder and Magee (1945)	12.0
Reines (1952)	18.5 ± 5
Brode (1964)	14.0 ± 3
Caudle (1965)	15.2 ± 2
Auxier (1977)	13.0 ± 2
Malik (1976)	15.8 ± 2
Malik (1980)	17.0 ± 4

*From canister data.

trajectory parameters. Some of the problems with the pressure-vs.-time method are:

- Gauge calibration [Caudle (1965), 3%]
- Gauge location relative to burst
  - Altitude
  - Height of burst
  - Aircraft ground speed
  - Wind speed vs. altitude
  - Bomb trajectory
  - Canister release and free-fall times
  - Canister drop speed
  - Atmospheric conditions
  - Separation distance of strike and instrumentation planes

These problems have largely been resolved, the notable exceptions being aircraft separation and the canister release times relative to the release of the bomb. The times were programmed by the bombardier, but no records have been located as to that programming. Resolution of the uncertainties of the other parameters, especially separation of the strike and the instrumentation aircraft, is also subject to debate. A very important parameter is the altitude of the two aircraft; the conflicting data are given in Table 6. Note the inconsistencies in Army Air Corps records, the navigator's log, and the weaponeer's log and recollection. We need the bombardiers' logs. Most of these problems may have been resolved. The log of the navigator of the *Enola Gay,* given by Marx (1967), was of considerable help, as was the weaponeer's log (Groueff, 1967). Besides aircraft altitude and speed, the other trajectory data required are time of fall, trail of the bomb (i.e., the difference between horizontal distance at burst and that of a trajectory in vacuum), and aircraft separation distance. The

TABLE 6

Data Sources Concerning Altitude of Aircraft

Hiroshima, Mission 13		
Strike Report	Altitude:	30,200 ft
Final Report	Pressure altitude:	30,200 ft
History of 509th Composite Group	Altitude of release:	31,600 ft
Navigator's log	True altitude:	31,060 ft
Weaponeer's log	Altitude:	32,700 ft
Nagasaki, Mission 16		
Strike Report	Altitude:	28,000 ft
Final Report	Pressure altitude:	28,900 ft
History of 509th Composite Group	Altitude of release:	31,600 ft
Weaponeer's recollection	Altitude:	~28,000 ft

time of fall and the trail of the bomb have largely been resolved by using data from the test drops at the Salton Sea test area (Site M). The use of these data permitted evaluation of the only free parameter in the classical projectile problem, in which drag is assumed proportional to the square of the speed. This assumption, good only to about Mach 0.9, is violated in the case of Little Boy during the last stages of flight. However, since the departure from vacuum conditions for this bomb is small, the assumption still should produce good results—the test data indicate a less than 2-sec difference in time of fall from vacuum conditions. For Fat Man, the assumption ought to be very good. Trajectory calculations are summarized in Table 7. In addition to the time of fall, the calculation gives the trail and the angle from vertical of the bomb at detonation. Neutron output calculations and Oak Ridge National Laboratory measurements both indicate that this is important.

My suggested best values for computing slant range and altitude of the gauges are summarized in Table 8. With these values and with graphs by Caudle (1965), I estimated the yield of the Hiroshima explosion from these parameters to be about 17 kt. (With an aircraft separation distance of 1 mile, as given in older records, the estimate is near 20 kt.) These have been altitude corrected. My previous estimate of 16 kt was not corrected.

TABLE 7

Trajectory Parameters

	Hiroshima		Nagasaki	
Height of burst, m (ft)	580 (1,903)		503 (1,650)	
Aircraft altitude, ft	32,700		28,900	
True air speed, mph	328		315	
Head wind, mph	∼0		1	
Trail, mil	53		180	
	Data	**Calculation**	**Data**	**Calculation**
Site M test data				
Altitude, ft	28,065		28,026	
Air speed, mph	315		300	
Time of fall, sec	43.11	43.4	47.70	47.71
Vertical speed, ft/sec	1,138	1,116	901	
Terminal speed, ft/sec		2,030		1,005
Angle at impact, degrees	12	17	10	11.5
Trail, ft	1,441	1,635	5,005	5,068
Combat conditions				
Time of fall, sec		45.5		47.0
Angle at explosion, degrees		17		12.2
Trail, ft		1,635		5,276

The positions of the canisters relative to the bursts, which are based on the parameter values of Table 8, are given in Table 9. The shock-wave arrival times relative to release, given in the last line, are the values taken from the records but have been increased by 1 sec as suggested by Alvarez (1963). The sonic-wave arrival times should be longer by about 1 sec. For Nagasaki the values agree, but for Hiroshima the sonic-wave arrival time should be increased by about 3 sec. Arbitrarily increasing the drop altitude or the aircraft separation distance would give a yield estimate of about 21 kt for Hiroshima, compared with 17 kt obtained with the "best" values of Table 8.

Further work—particularly if, e.g., the bombardiers' logs are found—could improve estimates based on the pressure-vs.-time canister data; more effort may, however, discredit those data.

A review of the paper by Penney, Samuels, and Scorgie (1970), who used the more extensive blast data base of the United States, may add to the credibility of estimates based on surface blast effects. That data base has considerable potential.

TABLE 8

"Best" Values of Parameters*

	Hiroshima	Nagasaki
Altitude, ft	32,700	28,900
Ground speed, mph	328	315
Bomb trail, ft	1,635	5,276
Height of burst, ft	1,903	1,650
Time of fall, sec	45.5	47.0
Aircraft separation distance, ft	300	300
Canister fall rate, ft/sec	16	16
Canister free-fall time, sec	1	1

*From canister data.

TABLE 9

Canister Position*

	Hiroshima	Nagasaki
Aircraft separation distance, ft	300	300
Horizontal distance, kft	20.1	15.3
Vertical distance, kft	29.5	26.0
Slant range, kft	35.7	30.1
Time of fall + sonic wave, sec	78.6	74.0
Time of fall + shock wave, sec	80.6	72.9

*From canister data.

Furthermore, it must be recognized that all radiochemically determined yields carry an uncertainty of 10%. Since our yield determinations are tied to radiochemically determined yields, they also carry an uncertainty of at least 10%. Fireball determination can now stand alone provided the data are good and the yield-to-mass ratio in the explosion was high. The data for Fat Man are not very good, and no such data exist for Little Boy.

The yield estimates for the two explosions are summarized in Table 10. The yield derived from estimates based on observed surface blast effects is about 12 ± 4 kt. Estimates based on other effects (calculations, thermal effects, and free-air blast observations) suggest a larger yield, about 15 ± 3 kt. Perhaps the Hiroshima explosion yield ought to be expressed in both ways.* The suggested yields are:

TABLE 10

Summary of Yield Estimates (in kilotons)

	Little Boy	Fat Man
Calculation	15 ± 5	22 ± 1
Radiation chemistry		21 ± 1.5
Fireball		22 ± 2
Thermal effects	15 ± 3	
Blast effects	12 ± 4	
Blast (Penney, Samuels, and Scorgie, 1970)	12 ± 1	22 ± 2
Canister P(T)	17 ± 4	
Suggested yield*	15 ± 3	22 ± 2

*Note: Current estimate for Hiroshima is 17 kt.

Fat Man	22 ± 2 kt
Little Boy	
Free-air blast	15 ± 3 kt
Surface blast	12 ± 4 kt

These yields must be regarded as tentative pending further review and the results of the yield calculations, together with the criticality experiments, which are currently under way at Los Alamos National Laboratory with supportive work at Lawrence Livermore National Laboratory and contractors to the Defense Nuclear Agency.

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*This dual approach was suggested by Gil Binninger, Science Applications, Inc., both before and during the symposium; it has merit.

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DISCUSSION

Binninger: Your Table 10 had a suggested yield for Hiroshima of 15 ± 3 kt. How did you use the other values listed in this table to obtain your suggested value?

Malik: I have no real rational way—I just feel that calculated yields and observed yields must be brought into some kind of rational relationship, and 15 seemed to be about the best number that would fit the experimental data; emphasis was primarily on the thermal data rather than on the blast. I think the blast—at least blast across the ground—is subject to terrain and blast loading effects. It certainly is not an ideal situation, and in my evaluation as well as in the evaluations by Lord Penney and by scientists at Oak Ridge, this surface was assumed to be ideal. I really do not believe that in these situations one can use ideal height-of-burst curves to estimate a yield based on blast effects.

Binninger: I would like to recommend that, in the spirit of statistical data analysis, since, for reasons that are not yet clear, the blast effects provide yield estimates of ~12 kt and the thermal calculations and canister data give values of ~15 kt, one might consider keeping those estimates separate and giving credibility to both data sets until whatever problem or discrepancy causing the difference is resolved. With regard to the structural analysis by Penney, Samuels, and Scorgie (1970), they discussed I beams that were identified at Hiroshima at three or four different locations. On the basis of a response analysis of the I beams, they obtained yield estimates of around 10 to 12 kt. Last year, through Defense Nuclear Agency sponsorship, Science Applications, Inc., had a number of I beams at some high explosive experiments in Canada, where we collected 37 data points. It was amazing how well we were able to predict the response of those structures by means of a one-degree-of-freedom analysis. Penney would have used this type of analysis. The other types of structures that Penney was investigating would be much more difficult to evaluate. I am pointing out that one can get a fairly accurate yield estimate, at least with I beams.

Malik: It is certainly true that I beams, flagpoles, and crushed cans were probably the best blast gauges available in Hiroshima and Nagasaki.

Jablon: Did you say that one of the reasons that you preferred 15 kt was the thermal data?

Malik: Yes.

Jablon: Your thermal data (Table 2) included one data point that you did not care for, and you omitted it. Are your thermal data, then, based on simple averaging of the remaining data points?

Malik: That is correct. I omitted the one noted from the evaluation.

Jablon: You did not attempt to decide which points looked more reliable than others?

Malik: No. Harry Hubbell at Oak Ridge presumably went through the data set and picked what he thought was the best, and I used that. Other data are also available from the Manhattan Engineer District observations, and use of that full data base raises the yield from about 15 to about 17 kt.

Jablon: I think Lord Penney (1970) said that, when he was considering what kinds of data might be suitable for estimating yields, he discussed thermal effects on granite but decided they were not reliable, because it was very hard to measure just what had happened to a piece of granite or to determine whether the effects on two different pieces of granite in the two cities at different distances were exactly equivalent. Would you comment on that?

Malik: I cannot comment on that because I have never been involved in evaluation of the observed effects. I can only take the word of someone who has presumably considered that, and I respect Harry Hubbell.

Jablon: Do you think it is reasonable to take any numbers that are written down and add them up and take the average and say, "That is the best estimate I can get"?

Malik: No. That is why I have not tried to make everything fit. I am simply trying to make an educated guess as to the most reasonable value for the yield and am discounting the blast-effects data which probably only set a lower limit.

Sinclair: I have a question about the yields that Dr. Malik was discussing. I do not know how much we can expect in terms of definition about yields. The equivalency to TNT presumably was evolved in the first place from blast information. Dr. Malik prefers the estimate based on thermal effects, and his judgment is certainly superior to that of any of the rest of us. What exactly does that mean in terms of equivalencies? The thermal effects must have some ratio to blast effects, which may not be a constant; and the radiation emitted from the bombs has some other ratio. Would Dr. Malik comment on exactly what these ratios mean in these circumstances?

Malik: Blast and thermal effects from these explosions ought to scale to better than 10% if we assume that blast can be evaluated from ideal conditions. Both ought to relate to a definition of nuclear yield as 10^{12} cal/kt. Yield determined from gamma-ray effects for such weapons ought to scale to better than 20%. The yield from neutron effects will not scale as well; estimates here must depend on calculations for the two explosions.

Reference

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Status of Los Alamos Efforts Related to Hiroshima and Nagasaki Dose Estimates

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ABSTRACT

Neutron and gamma-ray leakage spectra measurements will be made at the Los Alamos Critical Assembly Facility (LACAF) on the recently located Hiroshima bomb replicas in a near-critical configuration. These measurements, made with modern techniques, will provide a check for present-day cross sections and calculations. Similar measurements have been proposed on the Mark 9 weapon and on the Ichiban assembly.

Two-dimensional calculations of the neutron and gamma-ray outputs of the Hiroshima and Nagasaki weapons are in progress. Calculations of several air-transport experiments are also in progress. Calculated results are compared with experimental results. The neutron and gamma-ray output spectra of several devices tested in the atmosphere at the Nevada Test Site are being calculated. The results of these calculations will allow models of the debris cloud contribution to the total dose to be tested. Calculations have been completed for the Ranger Fox and the Upshot-Knothole Grable tests.

Measurements made at the LACAF, in conjunction with calculations, can be used to define the upper limit of the Hiroshima yield.

The neutron and gamma-ray doses assigned to the atomic bomb survivors at Hiroshima and Nagasaki must be accurate within some limits if conclusions drawn from studies of the survivors are to have value. The doses received by the survivors depend on the yields of the bombs, the specific radiation outputs of the bombs and of the bomb debris, and the transport of the radiation through the air and shielding around each survivor. In addition, the self-shielding of the body is important for many biological effects.

The accuracy of each element of the dose assignment procedure must be demonstrated by comparing calculated data with observed data from other pertinent experiments and Nevada tests as well as with physical data from Hiroshima and Nagasaki. Los Alamos National Laboratory (LANL) has started a small program to help resolve the question of the yield of the Hiroshima bomb, provide two-dimensional neutron and gamma-ray output for the Hiroshima and Nagasaki bombs, examine the validity of air-transport calculations, and provide neutron and gamma-ray output for some selected Nevada test shots. This program should help to derive dose assignments and to demonstrate their accuracy.

The goal of the LANL program is to provide certain missing weapons data so that the accuracy of dose calculations can be demonstrated.

YIELD OF THE HIROSHIMA BOMB

Yield data are available from test firings of three weapons nominally identical to the bomb exploded at Nagasaki (Fat Man); thus good estimates of the yield of the Nagasaki explosion have been made, as reported by John Malik (paper in this volume). The bomb exploded at Hiroshima, Little Boy, was of a radically different design. No test firings and no yield measurements of the Hiroshima-type weapon have been made. Estimates of the yield of the Hiroshima explosion by different investigators using different bits of data have ranged between 10 and 20 kt, also as reported by Malik (paper in this volume). The yield predicted for the Hiroshima explosion was 15 kt (Schiff, 1945).

To supplement the ongoing work by John Malik, George Kerr, and other investigators to resolve the different interpretations of blast, thermal, and canister data, LANL has started a program to establish theoretical limits on the yield of the Hiroshima explosion. Obviously, if the bomb was designed and the yield could be predicted in 1945 from the data available then, the yield can be calculated now with the wealth of data and calculational tools available. However, all the data available in 1945 are either no longer readily available or are expressed in terms not suitable for our current calculational schemes. One of the crucial—indeed critical—numbers available in 1945, i.e., the number that determines the criticality of the Little Boy assembly, is missing. Of course, the actual value used in 1945 for the infinitely tamped mass of ^{235}U is available as is the 1945 estimate for the criticality of Little Boy. Sufficient detail regarding the experiments and experiment analysis to allow estimation of the accuracy of the quoted values is missing. One very useful measurement was never made in 1945.

The yield of the Hiroshima bomb is very sensitive to the estimate of criticality. Sensitivity calculations using a number of cross-section sets available at LANL resulted in a spread of yields from 8 to 24 kt. The use of a subset of generally accepted cross sections resulted in a spread of calculated yields from 12 to 18 kt. These were strictly sensitivity studies with no significance to be attached to the central value.

Nuclear archeologists at LANL could probably turn up enough details of old experiments and analyses so that, by following a fairly complicated calculational program and doing perturbation analyses, they could provide a good theoretical estimate of the Hiroshima yield. This estimate, however, would be subject to fairly large uncertainties because of the many steps in the calculational program.

LANL can produce a theoretical estimate of the maximum yield of the Hiroshima explosion which is accurate to the nominal 10% quoted on directly measured yields by making the criticality measurement that was not done in 1945. The measurement will be done in the Los Alamos Critical Assembly Facility (LACAF), which is set up to allow two pieces of fissile material to be brought safely together into a critical configuration. Most of the critical-mass data available to the nuclear community have been produced in this facility.

In May 1981 four objects were located in field storage at LANL. Three of these were later identified by Harlow Russ, a retired employee, as nonfissile components of Little Boy weapons which had been retired from stockpile. The fourth was a training device without the proper materials. Harold Agnew, former director of LANL, had wisely stored these four samples. These components were transferred to the LACAF.

Several people in the laboratory knew of the existence of these components, but until the publicity in June concerning the Hiroshima and Nagasaki doses, they had not been aware of any interest in them.

Fissile parts have been ordered which will allow direct experimental determination of the criticality of the Little Boy in the LACAF. With this information calculation of the maximum yield is straightforward. The calculated yield is of necessity the maximum yield because of the possibility of a malfunction of the Hiroshima bomb. Even with this limitation, an accurate theoretical value for the maximum yield will be very valuable. A low theoretical value would exclude the higher yields inferred from results obtained by other techniques. A high theoretical value for the yield is not so useful, but it would be a strong indication that techniques inferring lower yields should be critically examined.

At this point the direct solution to the question of the Hiroshima yield always appears to be simply to fire one of the Little Boy replicas and measure the yield. However, because of the problems of measuring yields of this type of device in an underground environment, the directly measured yield would have very large error bars—larger than those associated with the program we are following. The interpretation of other test diagnostics coupled with calculations would reduce the error bars to 10%, but even a simple test would cost an order of magnitude more than the measurements in the LACAF.

The real problem in assigning dose is not the yield of the Hiroshima bomb but the neutron and gamma-ray output of the bomb and of the debris cloud. Measuring the two-dimensional outputs of the device would be even more expensive than measuring the yield in an underground environment, and measurements of debris clouds underground present real problems.

Two more activities, a program of comparing calculated spectra with spectra measured in the LACAF and a program of comparing calculated outputs with measured outputs from atmospheric shots at the Nevada Test Site, are described. These programs should be completed and the results examined before considering a Nevada experiment.

NEUTRON AND GAMMA-RAY OUTPUT

Los Alamos is doing two-dimensional calculations of the neutron and gamma-ray output spectra of both the Hiroshima and Nagasaki bombs. The Hiroshima bomb calculations are in progress. Because the Hiroshima bomb was much more two-dimensional than the Nagasaki bomb, which was nearly spherical, the Hiroshima bomb calculations are of greater interest.

Calculations of the neutron output of the Hiroshima bomb were done by W. Biggers of Los Alamos Scientific Laboratory (LASL) in 1962 with limited release to the people studying radiation effects. No reports of the results or other documentation of these calculations have been found, although some may exist in dead storage. These calculations are mentioned only because the neutron output appears to have been used before for Hiroshima dose estimates.

In 1975, W. E. Preeg of LASL did one-dimensional (spherical) calculations of the neutron and gamma-ray output spectra of both the Hiroshima and Nagasaki bombs for inclusion in the Defense Nuclear Agency (DNA) classified *Nuclear Weapons Output Handbook.* These output spectra were declassified by the Energy Research and Development Administration in 1976 and were published as a letter to C. P. Knowles (R&D Associates, Marina del Rey, Calif.). Because they comprise the starting point for all the dose reanalyses done to date, the letter is included as an appendix to this paper.

The Preeg letter contains, in addition to the output data, comparisons of dose as a function of distance with the dose inferences of Hashizume et al. (1967). The Preeg doses are not valid. The doses were not calculated in an air-over-ground geometry but came from a model for infinite air transport and were done for dry air; the debris contribution to the gamma-ray dose was not included, and the Nagasaki height of burst was incorrect.

This is all pointed out in the letter. The dose calculations were not pursued further.

With the revival of interest at LANL in the Hiroshima and Nagasaki doses, the one-dimensional calculations of output spectra done by Preeg were repeated with the computers, operating systems, codes, and cross sections currently in use at LANL. Six years is a long time, but the Preeg output spectra were confirmed.

The two-dimensional output calculations now being done will allow comparisons of activation data from locations close to ground zero, which could not be made before because of the anisotropy of the output of the Hiroshima bomb. These comparisons will be a new test of the validity of the calculations.

So that calibration data for the output spectra calculations can be provided, neutron and gamma-ray spectra measurements will be made at the LACAF on the Hiroshima replica in a near-critical configuration. These measurements, made with the best techniques available, will provide yet another check of codes and cross sections. The spectra measured at the LACAF on a cold static assembly are not the spectra of an exploding bomb. High-energy neutrons coming out of an exploding bomb penetrate a constantly changing thickness of material. Low-energy neutrons in an exploding bomb experience a thermal environment very different from that of a static assembly. Special-purpose codes have been developed to handle these effects.

Similar spectra measurements at the LACAF on the Mark 9 weapon and on the Ichiban assembly have been proposed. Most of the parts necessary for these experiments also exist.

Measurements on the Mark 9 assembly would provide a complete loop between the calculational procedures and the Nevada Test Site measurements.

Measurements on the Ichiban assembly would resolve a long-standing but little-known problem. In addition to there being two different calculated neutron spectra for the Ichiban experiment (which has been reported), there were two different neutron dose measurements made on the Ichiban assembly, of which only one was reported. Modern measurements would clear up the unreported discrepancy between the measurements.

AIR-TRANSPORT CALCULATIONS

Los Alamos National Laboratory has one of the premier transport calculational capabilities in the country. The Los Alamos MCNP code is a continuous-energy Monte Carlo code for coupled neutron and photon transport calculations which is in use at installations around the world. Cross sections for the code can be processed from several sources, including the Evaluated Nuclear Data Files (ENDF) library. Many of the features of the MCNP code and cross-section libraries are used in calculations of weapons output.

With the intention of doing Monte Carlo dose calculations when the two-dimensional output became available, several tests of the ENDF data for air transport were made. The first calculations were of the liquid-oxygen and liquid-nitrogen pulsed-sphere experiments done under DNA auspices at Lawrence Livermore Laboratory (LLL) (Wong et al., 1972). In these experiments a pulsed source of 14-MeV neutrons is generated in the center of a sphere of the material to be tested. Neutrons emerging from the surface of the sphere are counted by time-of-flight techniques. Typical results from these calculations with ENDF cross sections showed agreement to better than 10% with measured total neutron fluence between 2 and 14 MeV but discrepancies up to 50% in subintervals of the energy spectrum. Generally, the calculated fluences were low at high energies and high at low energies. The results of a typical calculation are shown in Fig. 1; the time-of-flight spectrum is shown in Fig. 1(a) and the energy spectrum, in Fig. 1(b). Calculations with the LLNL cross sections produced better comparisons, probably because these experiments had been used in the normalization of the LLNL cross sections. Even so, Fig. 2 shows discrepancies of 10% in total fluence between 2 and 14 MeV and of 30% in subintervals in comparisons of MCNP calculations using LLNL cross sections and measurements of a liquid-air pulsed-sphere experiment (Sidhu et al., 1978).

Somewhat discouraged by these results, which indicated that we were not calculating air-transported spectra very well and that the differences showed systematic trends, we turned to the "broomstick" experiments (Clifford et al., 1967). In these Oak Ridge National Laboratory experiments, a continuous source of neutrons from a port in the Tower Shielding Reactor II impinged on one end of a thin cylinder of the material under investigation. Neutrons emerging from the other end of the cylinder were counted in an energy discrimination mode. The result is a rather clean transmission experiment. Again calculations with ENDF cross sections of the neutron transmission through liquid oxygen and liquid nitrogen were disappointing. The calculated fluence tended to be low at high energies. In addition, the calculated valleys in the transmitted fluence through nitrogen did not agree in magnitude (factor of 2) or in energy (10 to 20%) with the observed valleys. The comparisons of calculations with observation are shown in Fig. 3, in which the "snake" is the error band of the observations and the circles are the calculational results.

Because the experiments described above are not directly appropriate for an air-over-ground geometry, we looked into the Aberdeen Proving

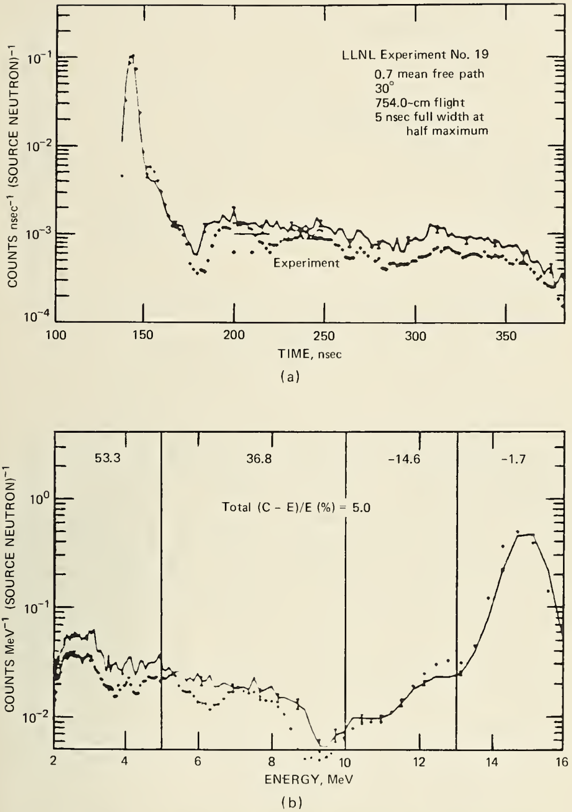

Fig. 1 Time-of-flight spectrum (a) and energy spectrum (b) from liquid-oxygen pulsed sphere (ENDF-5).

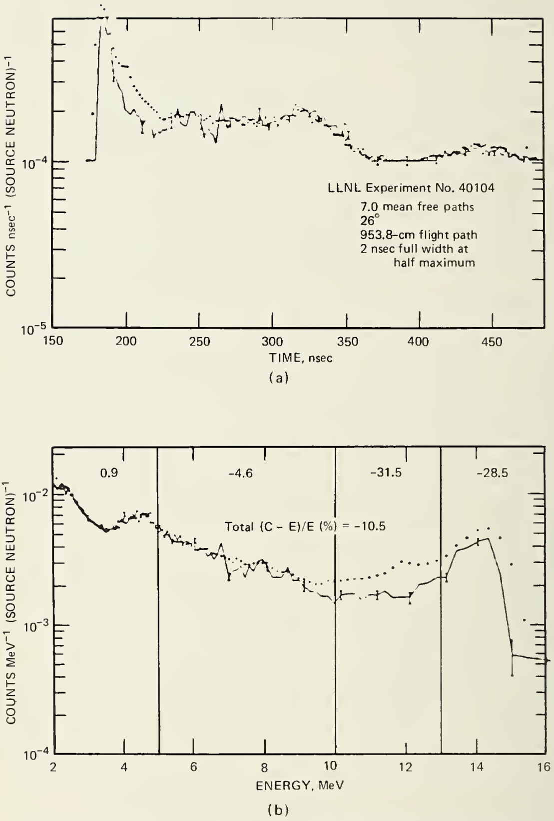

Fig. 2 Time-of-flight spectrum (a) and energy spectrum (b) from liquid-air pulsed sphere (ENDL-73).

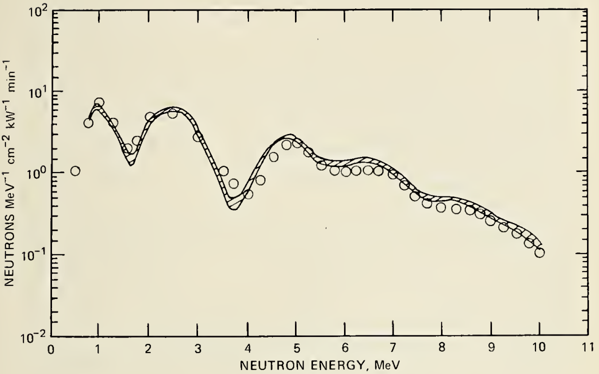

Fig. 3 Spectrum transmitted through liquid nitrogen.

Ground experiments, in which the U. S. Army Pulse Radiation Division (APRD) reactor was used as a source. In these experiments a fission reactor mounted 14 m above the ground provides a continuous source of neutrons, detectors are operated in an energy discrimination mode, and measurements are made at several distances from the reactor. Measurements have been made by several groups, and their results show differences of 40% (Robitaille and Hoffarth, 1980). However, if the measurements of the different groups are compared with the average of all the measurements, the individual ones are within 20% of the average over the energy range 0.6 to 10 MeV, as shown in Fig. 4. In contrast, the Los Alamos MCNP calculations of fluence using the ENDF cross sections fall well outside the 20% deviation from the average of the measurements and show a strong energy dependence. The Los Alamos calculated fluences are about 40% below the average of the measurements at high energies and about 40% above at low energies, as shown in Fig. 5. Also shown are the fluences calculated with the S_n discrete ordinate transport (DOT-3) code by the Defence Research Establishment, Ottawa (DREO). These show exactly the same pattern with neutron energy as the fluences calculated by the Monte Carlo code. This implies either that the cross sections are questionable or that all three experiment groups are having the same problem.

Because the ratio of calculated to observed fluence as a function of energy crosses unity, the calculated neutron kerma, being an integral over energy, has a smaller error than the calculated fluence as a function of

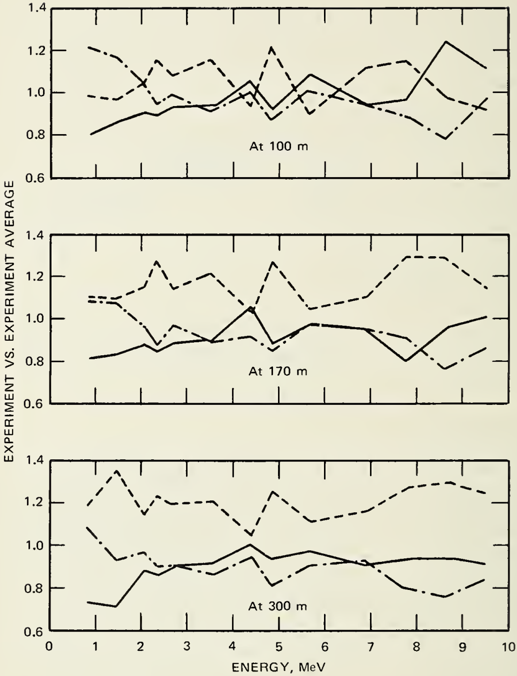

Fig. 4 Comparison of measured spectra from Army Pulse Radiation Division (APRD) reactor. ——, Defence Research Establishment, Ottawa (DREO)/av. – – –, APRD/av. –·–, Wehr Wisserschaftliche dienstelle (Federal Republic of Germany) (WWD)/av.

energy. Examination of the kermas reported by Robitaille and Hoffarth (1980) reveals an error of calculated neutron kerma of only about 15% at 300 m, rising to about 30% at 1000 m. This degree of accuracy in the neutron kerma may be completely adequate for the current study of doses. However, because of the spectral dependence of calculational error indicated by the pulsed-sphere and APRD experiments, caution must be exercised in the analysis of the sulfur activation data.

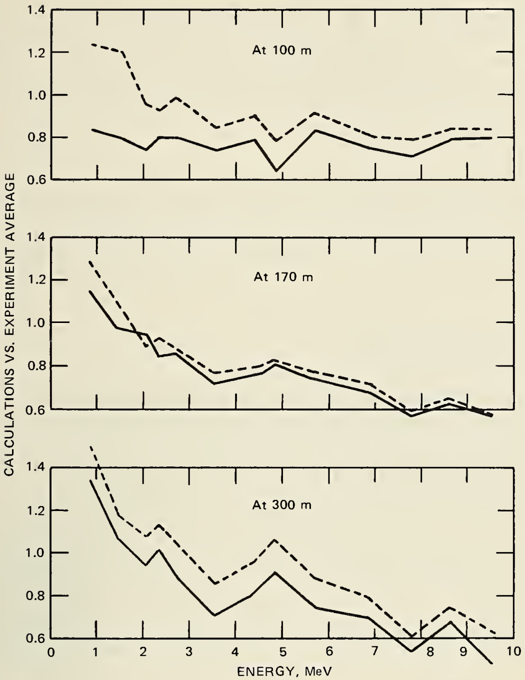

Fig. 5 Comparison of calculated spectra from Army Pulse Radiation Division (APRD) reactor. – – –, LANL, Monte Carlo code (MCNP). ——, Defence Research Establishment, Ottawa (DREO) DOT-3.

DEBRIS OUTPUT

Gamma rays from the debris cloud of a nuclear explosion contribute an appreciable fraction of the total dose on the ground at the ranges of interest at Hiroshima and Nagasaki. The modeling of the gamma-ray dose from the debris has not been done as accurately as could be desired. This topic is discussed by Kerr and Loewe (papers in this volume). To help in the calibration of more-accurate debris models, LANL will provide the calculated prompt neutron and gamma-ray output spectra for several Nevada Test Site explosions selected by D. C. Kaul and W. H. Scott, representing DNA, as having appropriate diagnostics. The total of the calculated air-transported prompt doses and the debris dose should match the observed doses. These dose (and spectra) comparisons will provide stringent tests of the overall accuracy of the Hiroshima and Nagasaki dose calculations.

Two-dimensional calculations have been completed for the Upshot-Knothole Grable explosion, and one-dimensional calculations have been completed for the Ranger Fox explosion. Other calculations will be completed as manpower permits. These calculations are not difficult, but locating the drawings and specifications for these old shots is time consuming.

ACKNOWLEDGMENTS

I wish to thank the following individuals at Los Alamos National Laboratory who have done all the work reported in this paper. X-4 Nuclear Applications Group: B. Rogers and R. Worlton for one-dimensional models and explosion calculations and J. Kammerdiener for two-dimensional explosion calculations of the Hiroshima bomb. X-5 Diagnostics Physics Group: R. Streetman for the calculations of the radiation outputs of the explosions. X-6 Monte Carlo Group: P. Soran for providing cross-section sets; R. Seamon for providing, modifying, and checking cross sections; R. Little for the "broomstick" calculations; and G. Estes for the pulsed-sphere and APRD calculations and the method of data presentation. Q-14 Critical Assemblies Group: R. Malefant for enthusiastic support from the Critical Assembly Facility. NSP/T&V Test and Verification Office: J. Malik for sharing his encyclopedic knowledge of measurements made on nuclear explosions and H. Russ (retired) for locating lost drawings. Funding for the output calculations was provided by the Defense Nuclear Agency.

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Clifford, C. E., et al., 1967, Measurements of the Spectra of Uncollided Fission Neutrons Transmitted Through Thick Samples of Nitrogen, Oxygen, Carbon and Lead: Investigation of the Minima in Total Cross Sections, *Nucl. Sci. Eng.*, 27: 299-307.

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DISCUSSION

Ellett: In your two-dimensional calculations of neutron and gamma-ray yield, did you consider the dynamic disassembly of the mechanism?

Whalen: Yes. Static spectral measurements have nothing to do with the spectra from the exploding bombs.

Auxier: Clarification would be aided by reexploding a Little Boy device. I agree with your analysis, but if we could do an aboveground explosion, we could solve the main problems that brought us together here, namely, the spectrum and the neutron : gamma ratios; these would be reproduced. The thing that would not be resolved by refiring would be the yield, but the discrepancy between 12.5 and 15 kt is fairly small, well within the error bar, and I think that John Malik, as he looks at it for another year or two, will zero in on 12.5 kt anyway. However, there would be a lot to gain if we could ever refire it. I was surprised that you had components of the old weapons all the time, during the years when no one would admit that they could copy those weapons.

Whalen: We did have them. They are there, and three people have told me that they knew all the time.

Sinclair: Am I correct that in a month there will be a new version of the Preeg spectrum, which is from a cylindrical mockup and which includes any cross-sectional changes you are going to make?

Whalen: Yes.

Sinclair: Will that be written up in a couple of months?

Whalen: We hope to have a preliminary spectrum out in a month, but before we can publish it, we will have to get it declassified. However, even before that we want to get together with our colleagues at Livermore to determine if it is as good a spectrum as can be obtained nowadays.

Sinclair: May I urge you to make sure that people stay on this job because I think it is very important that we get it done.

Whalen: I have no control over that.

Auxier: You mentioned a two-dimensional calculation with all the cross sections, etc., but in reality you are going beyond that. You are using the real weapon, mocked up, with modern cross sections and multidimensional calculations with all the hydrodynamics, right?

Whalen: Yes.

Auxier: You will have calculations within the next few months which will be independent of any other thing that has ever happened, right? You are going to present data which are the result of straightforward calculations and which are not normalized to anything on earth, except maybe a yield?

Whalen: Yes.

Auxier: Then the comparison with the critical assembly does not count anymore, right? Just the yield and your calculations ought to be the whole package—if it is not, we are not solving anything.

Whalen: No, no, no. Whether we are going in the right direction or the wrong direction can be judged only by comparison of calculations with experiments.

Auxier: I would like to think that at this stage we could take anybody's cross-section code and do a calculation that is not very far off. It is one thing to say that in 1965 the cross sections for gamma reactions and nitrogen were not known accurately, but at this stage they are surely known within a few percent and should not need to be normalized with a critical leakage experiment.

Whalen: I tried to show that there still are problems with the cross sections for air transport. The critical leakage experiments will show whether there are problems with the cross sections for the bomb materials.

Auxier: You make me feel a lot better about these things than I did a couple of years ago. On the other hand, you make me uneasy about what we are going to know in a year from now. Physical cross sections are physical parameters and, given the energy, are invariant. What is changing are our perceptions or our measurements or our calculations of cross sections, and so we take different values. My question is, "Are the cross sections that we are using based on experimental values, or are they calculated?"

Whalen: We are using the Evaluated Nuclear Data File cross sections.

Auxier: We in this room anxiously await your work, and I will be delighted to see it. My uneasiness is related to the question, "Once we see your work, where will that leave us?" Instead of the final stage, what stage will we be in?

APPENDIX*

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(Contract W-7405-ENG-36)
P. O. Box 1663
Los Alamos, New Mexico 87545

IN REPLY
REFER TO: TD-3
MAIL STOP: MS-232

April 5, 1976

Dr. C. P. Knowles
R and D Associates
P. O. Box 9695
Marina del Rey, CA 90291

THRU: R. N. Thorn, TD-DO

Dear Skip,

SUBJECT: NEUTRON AND GAMMA-RAY OUTPUT FOR FAT MAN AND LITTLE BOY

There have been several requests for the neutron and gamma-ray spectra out of the Fat Man and Little Boy devices. Since this data is unclassified, I have decided to issue it as an unclassified letter. This is the same data that was given in my letter to you on October 22, 1975 (TD-3:75-87).

Some of the overall device parameters such as yield, mass, total neutron and gamma-ray output are given in Table I for both devices. The only change in this table since my previous letter is the inclusion of two other references for the "observed" Little Boy yield. The neutron and gamma-ray spectra are given in Table II and III, respectively.

These results have also been compared with measurements of dose* vs range. The HEART code was used to transport the neutron and gamma rays through the air. Most of the gamma-ray dose results from (n,γ) reactions in the air as opposed to direct gamma rays from the device. No effects of the ground were considered. The neutron and gamma-ray doses for Hiroshima (Little Boy) are given in Fig. 1 and 2, respectively. The neutron and gamma doses for Nagasaki (Fat Man) are given in Fig. 3. The neutron measurements were obtained from Co activation in steel and the gamma-ray measurements were made from roof tile.

A comparison of the calculated and measured doses still leave some unanswered questions. For Hiroshima, the neutron doses are in good agreement and the gamma-ray doses are in good agreement at larger distances. The calculations of the gamma-ray dose do not include fission product gamma rays which probably explains the lower dose at small distances. For Nagasaki, the calculated doses are low for both neutrons and gamma-rays.

---

*T. Hashizume, et al., "Estimation of the Air Dose From the Atomic Bombs in Hiroshima and Nagasaki," Health Physics 1967, Vol. 13, pp. 149-161.

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*This appendix has been retyped verbatim from the original copy.

C. P. Knowles April 5, 1976

There are several possible explanations for these discrepancies. The Fat Man device (Nagasaki) had a very large output of low-energy neutrons. The transport of these neutrons and the resulting gamma-ray production in the air involves times which are comparable with the time for fireball growth. The effect of the fireball growth was not considered in the calculations. Another possibility is that the yield of Little Boy (Hiroshima) was considerably less than calculated, as suggested in some of the references in Table I. This would result in both calculations being lower than the observed values which would suggest an error in the conversion factors of activation to dose or neutron flux to dose. Finally, there is some question of the height of burst for Fat Man. These calculations assumed that it was 580 m. If the height of burst was only 500 m, the observed and calculated doses would be in much better agreement.

These discrepancies can probably be resolved. John Malik (J-DOT, LASL) has mentioned to me that other dose measurements exist on devices that were either the same or very similar to the Fat Man. By comparing these measurements with our calculations, we could determine if the Nagasaki comparisons are accurate and hence whether the Hiroshima comparisons are valid at the calculated yield.

I hope this information will be useful to you.

Sincerely yours,

W. E. Preeg
Alternate Group Leader, TD-3

cc: Major R. A. Skarupa, DNA
Capt. R. E. Wiley, AFTAC
J. A. Auxier, HNL
J. V. Pace, HNL
L. J. Deal, Hq, ERDA
E. A. Straker, SAI
O. T. Vik, LLL
T. W. Dowler, ADWP-2, MS-632
J. Malik, J-DOT, MS-672
T. L. Talley/D. R. Worlton, TD-4, MS-250
R. M. Henson, TD-2, MS-220
P. P. Whalen, TD-3
ISD-5 (2)

TABLE I
FAT MAN AND LITTLE BOY DEVICE PARAMETERS

	Fat Man	Little Boy
Calculated Yield (kt)	24.9	19.5[b]
Observed Yield (kt)[a]	22	14 - 18.5
Mass (kg)	4700	4050
Neutron Output (moles/kt)	0.28	0.21
Average Energy of Leakage Neutrons (MeV)	0.010	0.315
Gamma-Ray Efficiency (%)	0.095	0.044

[a] Fat Man measurement based on rad chem for Able event Crossroads, Trinity. Little Boy yields are given in the following reports:
LA-1398, "Yield of the Hiroshima Bomb," April 18, 1952.
NOLTR-65-143, "Yield of the Hiroshima Weapon," December 27, 1965.
RM-4193-PR, "Yield of the Hiroshima Bomb Derived from Pressure Record," September 1964.

[b] Calculated yield used in output calculations.

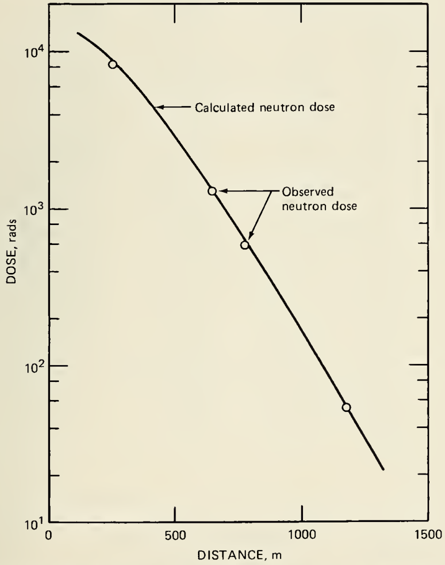

Fig. 1 Air dose due to neutron radiation in Hiroshima as a function of horizontal distance from ground zero.

TABLE II

NEUTRON OUTPUT SPECTRA

Energy Group (MeV)		Neutron Output	
		Fat Man	Little Boy
6.07	7.79	1.33E+21	1.86E+21
3.68	6.07	2.74E+21	7.11E+21
2.865	3.68	2.20E+21	8.56E+21
2.232	2.865	3.77E+21	1.52E+22
1.738	2.232	2.96E+21	2.35E+22
1.353	1.738	2.85E+21	3.01E+22
0.823	1.353	5.91E+21	1.01E+23
0.500	0.823	4.13E+21	2.33E+23
0.303	0.500	1.97E+21	3.61E+23
0.184	0.303	2.03E+21	3.21E+23
6.76E-2	0.184	2.46E+21	5.40E+23
2.48E-2	6.76E-2	1.24E+21	2.31E+23
9.12E-3	2.48E-2	1.32E+21	3.52E+23
3.35E-3	9.12E-3	1.58E+21	7.77E+22
1.235E-3	3.35E-3	1.70E+21	6.25E+22
4.54E-4	1.235E-3	4.21E+23	4.12E+22
1.67E-4	4.54E-4	1.52E+24	1.12E+22
6.14E-5	1.67E-4	1.32E+24	3.29E+21
2.26E-5	6.14E-5	6.62E+23	7.34E+20
8.32E-6	2.26E-5	2.10E+23	----------
3.06E-6	8.32E-6	5.60E+22	----------
1.13E-6	3.06E-6	2.38E+22	----------
4.14E-7	1.13E-6	1.54E+21	----------

TABLE III
GAMMA-RAY OUTPUT

Energy Group (MeV)	Gamma-Ray Output	
	Fat Man	Little Boy
9 – 10	2.37E+20	3.25E+20
8 – 9	9.12E+19	3.07E+20
7 – 8	2.37E+22	1.01E+22
6 – 7	6.38E+21	2.65E+21
5 – 6	4.54E+21	2.05E+21
4 – 5	1.11E+22	4.83E+21
3 – 4	1.75E+22	7.37E+21
2 – 3	4.84E+22	1.04E+22
1 – 2	9.09E+22	1.55E+22
0.5 – 1	2.44E+22	2.80E+22
0.1 – 0.5	4.99E+21	1.22E+21

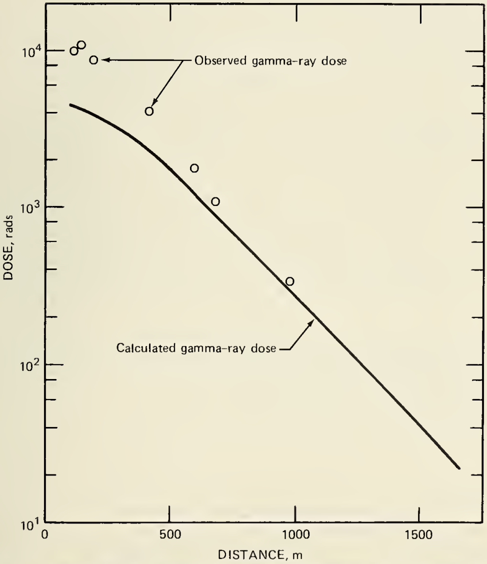

Fig. 2 Air dose due to gamma-ray radiation in Hiroshima as a function of horizontal distance from ground zero.

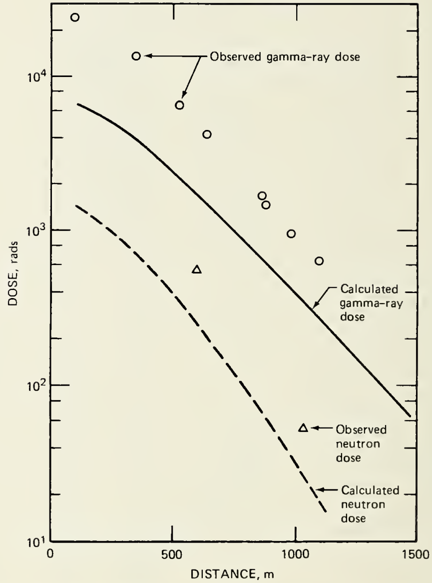

Fig. 3 Air dose due to neutron and gamma-ray radiation in Nagasaki as a function of horizontal distance from ground zero.

Transport in an Air-over-Ground Environment of Prompt Neutrons and Gammas from the Hiroshima and Nagasaki Weapons

J. V. PACE III, J. R. KNIGHT, and D. E. BARTINE
Oak Ridge National Laboratory, Oak Ridge, Tennessee

ABSTRACT

Much of the work on radiation shielding in the last two decades has been aimed at developing adequate data on transport methods and cross sections to describe the numerous prompt-neutron and the prompt and secondary gamma-ray interactions through the various materials. When adequate experimental data are available, the calculational results can be benchmarked. In the absence of such test data, however, one must rely on results obtained from the particle-transport calculations. The two most accurate methods for these calculations are the discrete-ordinates S_n method and the Monte Carlo method.

This paper is concerned with the application of the S_n method for approximating a solution to the Boltzmann transport equation in an air-over-ground two-dimensional, cylindrical geometry as applied to the Hiroshima and Nagasaki environments. The calculational sequence used to determine any response that depends on the transported particle fluence is as follows:

- Determination of the proper energy and angular source distribution, the air and ground cross sections to be used, and the proper material compositions.
- Determination of the suitable response functions, which may require adjoint transport calculations, inputting data to the appropriate transport codes, mitigating any ray effects, and calculating the desired free-field dose responses. For complicated geometries, coupled transport calculations may be required.

Additional tasks that should be completed before acceptance of any reevaluation of dosimetric effects include the best possible air-over-ground transport calculations using the most reliable weapon source data together with a more realistic ground composition; an air-over-ground sensitivity analysis to indicate the relative importance of source description components; cross sections for individual elements as a function of energy and reaction type, source height, and ground range; and transport calculations and comparisons of several Nevada Test Site weapons shots and the Ichiban, BREN, and Burlington AEC Plant bomb experiments for benchmark purposes.

This paper describes techniques for calculating the prompt-radiation fields at Hiroshima and Nagasaki and also presents some preliminary results.

TRANSPORT CALCULATIONAL TECHNIQUES

Transport calculations of radiation from nuclear weapons in an air-over-ground environment are normally accomplished by using either a Monte Carlo technique or a discrete-ordinates S_n (sulfur activation by fast neutrons) technique. For geometries that cannot be described in two dimensions and for time-dependent problems, the Monte Carlo method is used. However, if the problem can be described in two dimensions, is not time dependent, and requires a knowledge of the particle fluence throughout the system, then the discrete-ordinates S_n method can be used. This radiation transport work was accomplished with the one- and two-dimensional discrete-ordinates transport codes, ANISN and DOT, written by Engle (1967) and Rhoades et al. (1979), respectively.

CALCULATIONAL PROCEDURES

The Hiroshima and Nagasaki weapons neutron and gamma-ray leakage spectra were obtained from Preeg (1976) and are shown in Tables 1 and 2. These data were placed in the neutron and gamma-ray energy group structure of the data given by Bartine et al. (1977), in the Defense Nuclear Agency (DNA) library, which contains the standard group structure we have used. A flat weighting was used in the transformation.

An initial calculational effort in late 1976, with use of the neutron and gamma-ray data given in the DNA library and the appropriate input data (Table 3) as derived from Malik (1976) and shown in Table 4, gave neutron results that were 50% higher than those obtained later by Loewe and Mendelsohn (1980). Investigation of this disagreement revealed that the 1/E weighted DNA cross sections did not properly transport the neutron leakage spectrum at Hiroshima but they did properly transport that at Nagasaki. Nevertheless, improved broad group sets of cross sections for both the Hiroshima and Nagasaki environments were created from the Vitamin-C 171 neutron/36 gamma-ray fine group cross sections of Roussin et al. (1979). These new sets were produced by zone weighting and collapsing the fine group set into the DNA group structure with the ANISN one-dimensional transport code. One-dimensional calculations using the new cross-section sets showed a maximum deviation in the neutron results of only 8% when compared with those of Loewe and Mendelsohn (1980) and the Vitamin-C 171 neutron/36 gamma-ray calculations.

An anomaly known as the ray effect occurs in two-dimensional R-Z cylindrical discrete-ordinates geometry if the source and the detector are small, the scattering mean free path is large compared with the space mesh, and portions of the space mesh are not intersected by at least one of the discrete polar angles. If ray effects are dominant, then the particle flu-

TABLE 1

Neutron Leakage Spectra*

	Neutron output	
Energy group, MeV	**Fat Man**	**Little Boy**
6.07 to 7.79	1.33×10^{21}	1.86×10^{21}
3.68 to 6.07	2.74×10^{21}	7.11×10^{21}
2.865 to 3.68	2.20×10^{21}	8.56×10^{21}
2.232 to 2.865	3.77×10^{21}	1.52×10^{22}
1.738 to 2.232	2.96×10^{21}	2.35×10^{22}
1.353 to 1.738	2.85×10^{21}	3.01×10^{22}
0.823 to 1.353	5.91×10^{21}	1.01×10^{23}
0.500 to 0.823	4.13×10^{21}	2.33×10^{23}
0.303 to 0.500	1.97×10^{21}	3.61×10^{23}
0.184 to 0.303	2.03×10^{21}	3.21×10^{23}
6.76×10^{-2} to 0.184	2.46×10^{21}	5.40×10^{23}
2.48×10^{-2} to 6.76×10^{-2}	1.24×10^{21}	2.31×10^{23}
9.12×10^{-3} to 2.48×10^{-2}	1.32×10^{21}	3.52×10^{23}
3.35×10^{-3} to 9.12×10^{-3}	1.58×10^{21}	7.77×10^{22}
1.235×10^{-3} to 3.35×10^{-3}	1.70×10^{21}	6.25×10^{22}
4.54×10^{-4} to 1.235×10^{-3}	4.21×10^{23}	4.12×10^{22}
1.67×10^{-4} to 4.54×10^{-4}	1.52×10^{24}	1.12×10^{22}
6.14×10^{-5} to 1.67×10^{-4}	1.32×10^{24}	3.29×10^{21}
2.26×10^{-5} to 6.14×10^{-5}	6.62×10^{23}	7.34×10^{20}
8.32×10^{-6} to 2.26×10^{-5}	2.10×10^{23}	
3.06×10^{-6} to 8.32×10^{-6}	5.60×10^{22}	
1.13×10^{-6} to 3.06×10^{-6}	2.38×10^{22}	
4.14×10^{-7} to 1.13×10^{-6}	1.54×10^{21}	

*From W. E. Preeg, Los Alamos Scientific Laboratory, letter to C. P. Knowles (R&D Associates), Subject: *Neutron and Gamma-Ray Output for Fat Man and Little Boy*, 1976.

ence will be too large in mesh spaces which are intersected by the discrete polar angles and too small in mesh spaces which are not. This effect can be mitigated (1) by using the first-collision source method, which moderates the rays by placing an analytic first-collision source in each space mesh, or (2) by using a higher order angular quadrature (i.e., more polar angles). For most cases the first method will ensure accurate results. However, if the small or point source in turn produces another isolated source (e.g., secondary gamma-ray production) which appears as another small source, then a combination of a first-collision source and a higher order angular quadrature must be used to obtain the proper particle fluences.

TABLE 2

Gamma-Ray Leakage Spectra*

Energy group, MeV	Gamma-ray output	
	Fat Man	Little Boy
9 to 10	2.37×10^{20}	3.25×10^{20}
8 to 9	9.12×10^{19}	3.07×10^{20}
7 to 8	2.37×10^{22}	1.01×10^{22}
6 to 7	6.38×10^{21}	2.65×10^{21}
5 to 6	4.54×10^{21}	2.05×10^{21}
4 to 5	1.11×10^{22}	4.83×10^{21}
3 to 4	1.75×10^{22}	7.37×10^{21}
2 to 3	4.84×10^{22}	1.04×10^{22}
1 to 2	9.09×10^{22}	1.55×10^{22}
0.5 to 1	2.44×10^{22}	2.80×10^{22}
0.1 to 0.5	4.99×10^{21}	1.22×10^{21}

*From W. E. Preeg, Los Alamos Scientific Laboratory, letter to C. P. Knowles (R&D Associates), Subject: *Neutron and Gamma-Ray Output for Fat Man and Little Boy*, 1976.

TABLE 3

Atmospheric Conditions at Hiroshima and Nagasaki

	Hiroshima atmospheric conditions		Nagasaki atmospheric conditions	
	At 0 m	At 570 m	At 0 m	At 503 m
Pressure, mb	1018	950	1014	955
Temperature, °C	26.7	23.0	28.8	25.6
Relative humidity, %	80	71	71	67

After the first-collision source has been obtained from input of the proper cross sections and particle source, the total collided-particle fluence is calculated with the DOT code developed by Rhoades et al. (1979). Any calculations that required a higher order quadrature in addition to a first-collision source were run with a low-order quadrature until convergence and then were restarted with the high-order quadrature until convergence was again obtained (after one more iteration). The final result (collided-plus uncollided-particle fluence) was then available to convolute with any response factors available in the same energy group structure as the fluence.

TABLE 4

Air Compositions (atoms per barn-centimeter)

Element	Ground	Little Boy air density			Fat Man air density		
		At 0 to 117.9 m	At 117.9 to 503.5 m	At 503.5 to 1035 m	At 0 to 116.5 m	At 116.5 to 500.8 m	At 500.8 to 1035 m
H	9.766×10^{-3}	1.371×10^{-6}	1.177×10^{-6}	8.741×10^{-7}	1.404×10^{-6}	1.203×10^{-6}	8.890×10^{-7}
N		3.827×10^{-5}	3.723×10^{-5}	3.557×10^{-5}	3.781×10^{-5}	3.681×10^{-5}	3.541×10^{-5}
O	3.479×10^{-2}	1.096×10^{-5}	1.059×10^{-5}	9.993×10^{-6}	1.087×10^{-5}	1.050×10^{-5}	9.956×10^{-6}
Al	4.883×10^{-3}	–*	–	–	–	–	–
Si	1.160×10^{-2}	–	–	–	–	–	–

*A dash signifies that the elements do not exist in the particular mixture, which is air.

PRELIMINARY RESULTS

Response factors used to produce the following results came from the DNA library of Bartine et al. (1977). Figures 1 to 8 show free-in-air tissue kerma isodose plots in the Hiroshima (Little Boy) and Nagasaki (Fat Man) environments. All plots have been normalized to one source-leakage neutron or gamma ray. Figures 3 and 7 show the development of ray effects, whereas Figs. 4 and 8 show how such effects were mitigated by using a high-order quadrature.

Plots of neutron and secondary gamma-ray spectra are shown in Figs. 9 to 12. The fluence has been multiplied by the slant range squared (R^2) and has been changed from "per source neutron" to "per kiloton." Figures 9 and 11 show the progress of neutron equilibrium as the ground range is increased. Figures 13 to 16 show the contribution of neutrons in specific energy ranges to the total fluence and total kerma. From Figs. 13 and 15 one sees how important the thermal neutron fluence is to the total neutron fluence. However, because the free-in-air tissue kerma response is a high-energy response, the kermas as shown in Figs. 14 and 16 are driven by the high-energy neutron fluence. In particular, the kerma due to neutrons greater than or equal to 2.5-MeV eventually plays the major role in determining the relaxation length. Thus in Hiroshima the relaxation length approached a constant value further from ground zero than it did in Nagasaki.

To determine the effects of humidity on the radiation environments in the two cities, we made several one-dimensional calculations with the results shown in Figs. 17 to 20. Figures 17 and 18 show the slant-range-squared neutron kerma in infinite Nevada-type air (low humidity) and Hiroshima-type air (high humidity), which resulted from the Hiroshima (Little Boy) and Nagasaki (Fat Man) neutron sources. The three-digit numbers next to some symbols are the approximate relaxation lengths at those points. Figures 19 and 20 show the effect of moisture on gamma-ray production for the two air environments.

Additional one-dimensional air-over-ground slab calculations were made with and without gamma-ray production in the ground cross sections. These results showed that only 13% of the secondary gamma-ray kerma was due to production in the ground. This percentage is much higher with more modern sources at lower burst heights.

CONCLUSIONS

The following generic sensitivity results have been discussed: importance of ray smoothing, sensitivity of neutron kerma to high-energy particles, sensitivity of neutron and gamma-ray kerma to source characteriza-

(Text continues on page 156.)

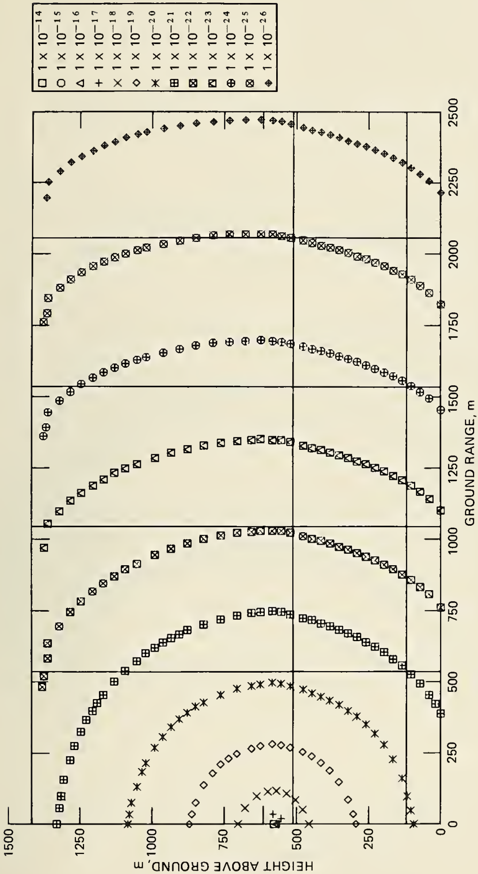

Fig. 1 Hiroshima neutron free-in-air tissue kerma (rads per source neutron).

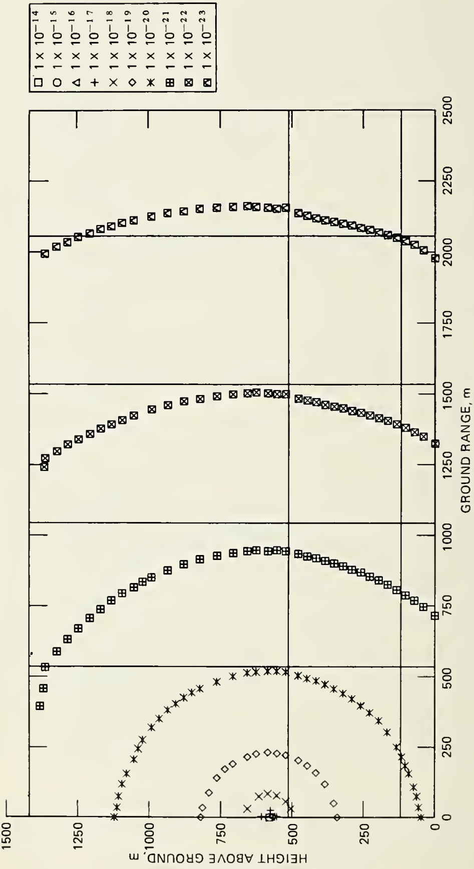

Fig. 2 Hiroshima prompt gamma free-in-air tissue kerma (rads per source gamma).

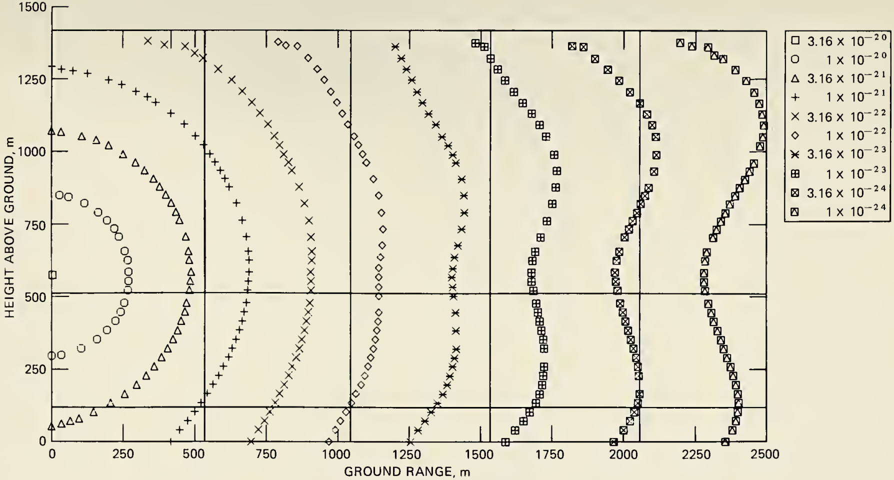

Fig. 3 Hiroshima secondary gamma free-in-air tissue kerma before ray smoothing (rads per source neutron).

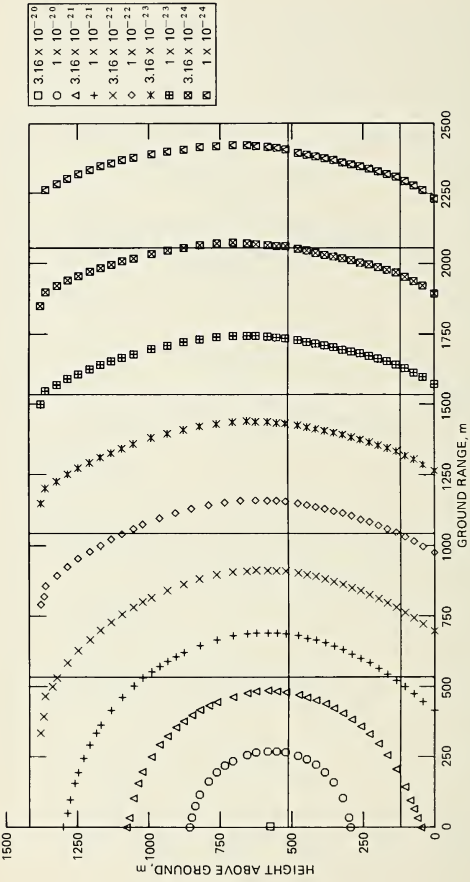

Fig. 4 Hiroshima secondary gamma free-in-air tissue kerma after ray smoothing (rads per source neutron).

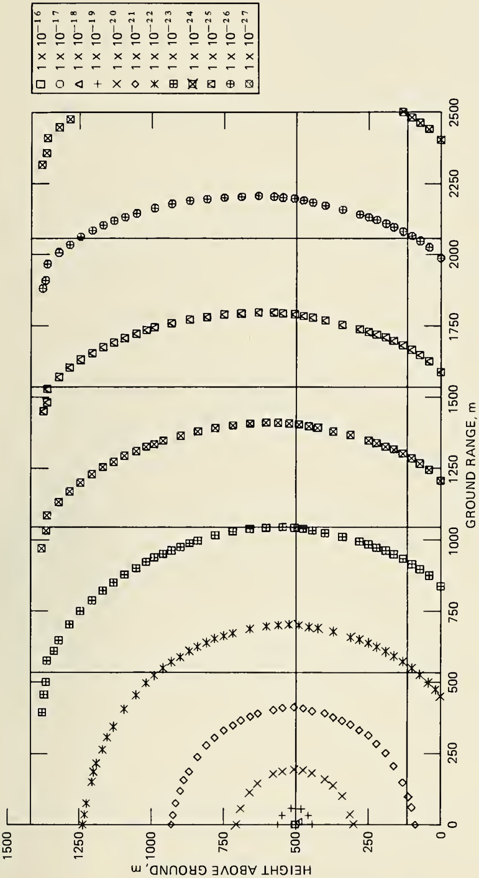

Fig. 5 Nagasaki neutron free-in-air tissue kerma (rads per source neutron).

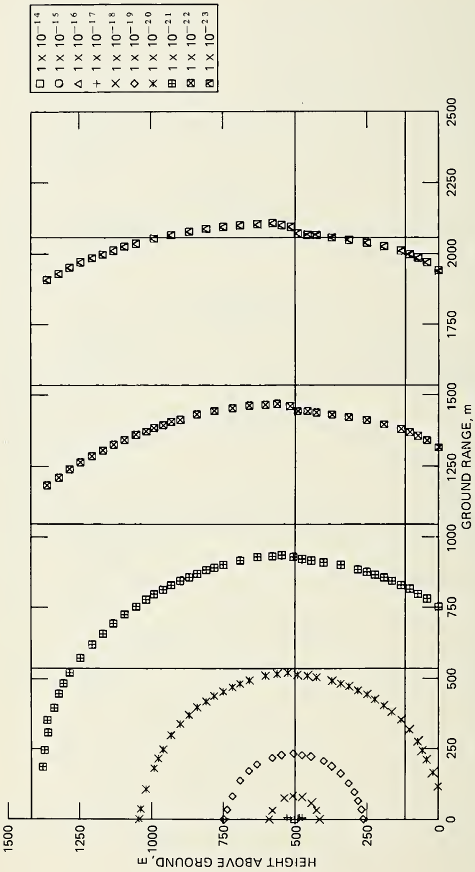

Fig. 6 Nagasaki prompt gamma free-in-air tissue kerma (rads per source gamma).

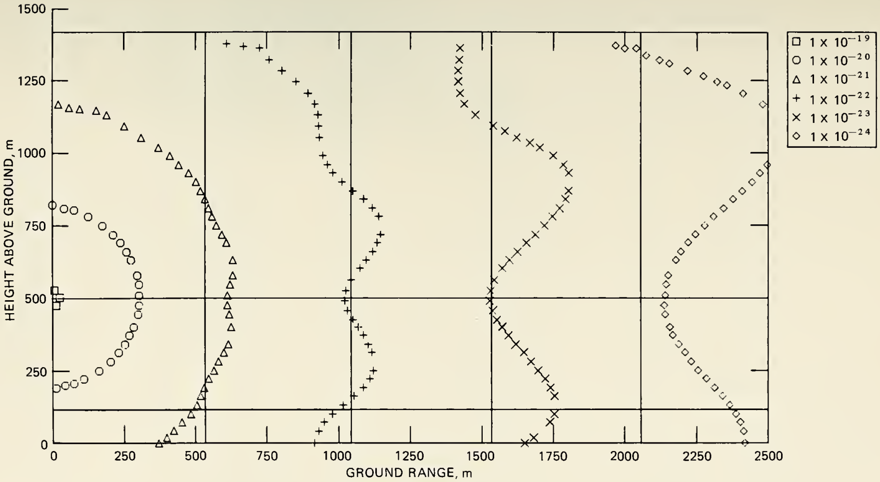

Fig. 7 Nagasaki secondary gamma free-in-air tissue kerma before ray smoothing (rads per source neutron).

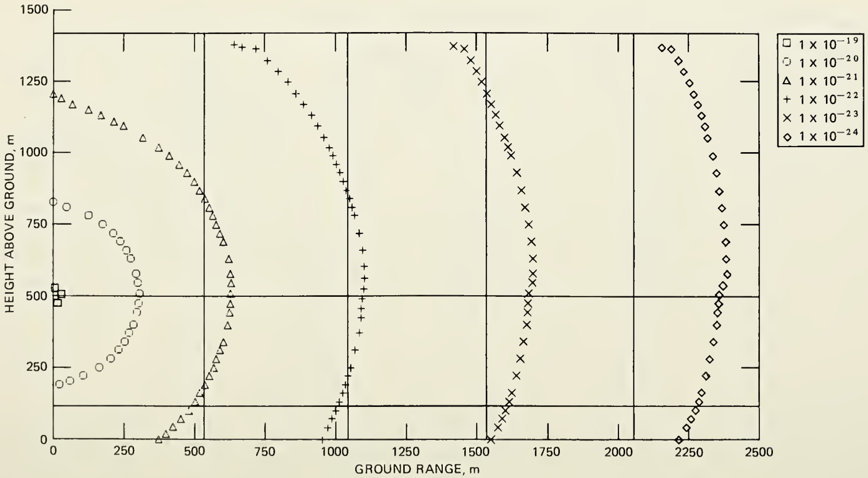

Fig. 8 · Nagasaki secondary gamma free-in-air tissue kerma after ray smoothing (rads per source neutron).

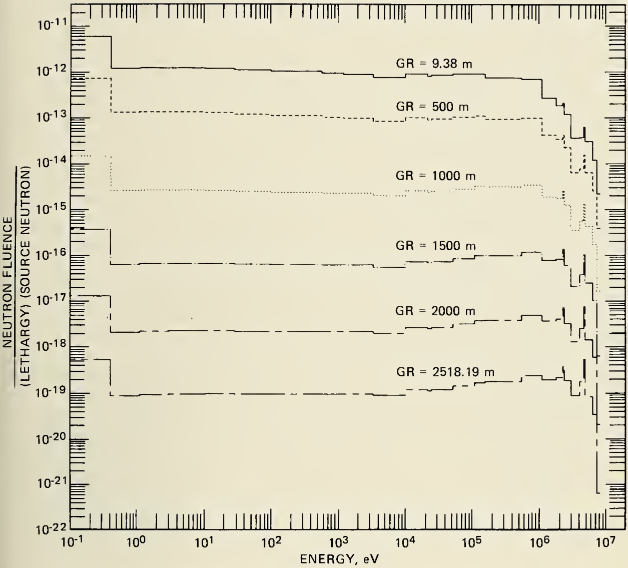

Fig. 9 Hiroshima neutron spectra at various ground ranges (GR).

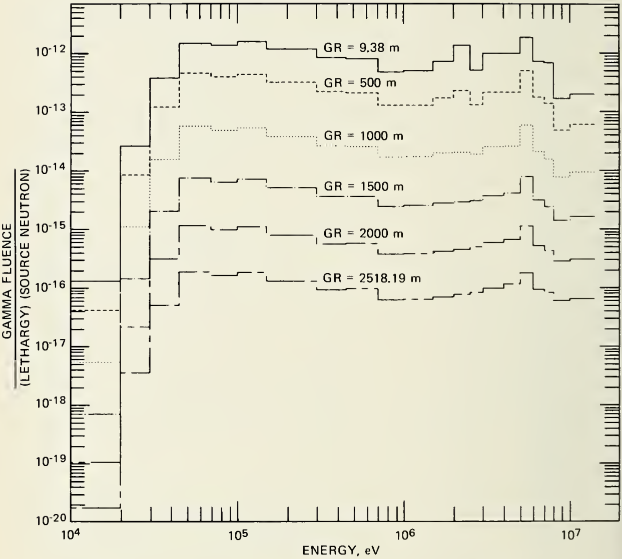

Fig. 10 Hiroshima secondary gamma spectra at various ground ranges (GR).

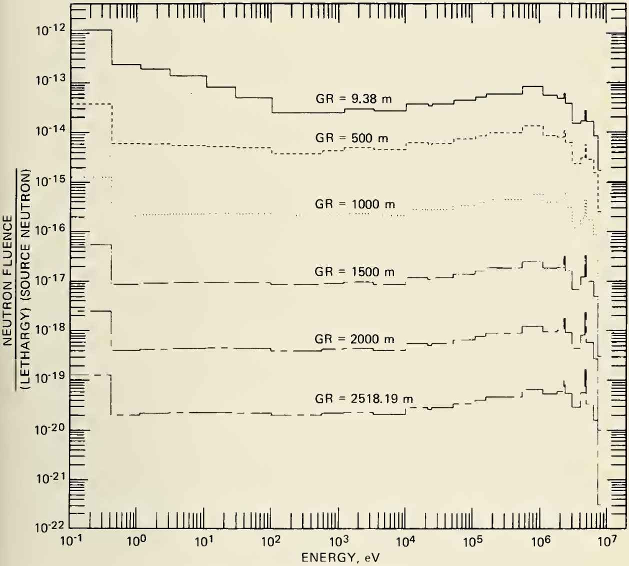

Fig. 11 Nagasaki neutron spectra at various ground ranges (GR).

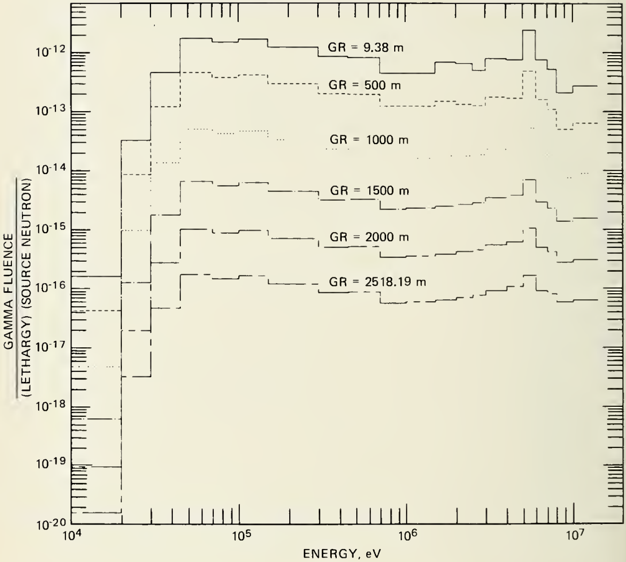

Fig. 12 Nagasaki secondary gamma spectra at various ground ranges (GR).

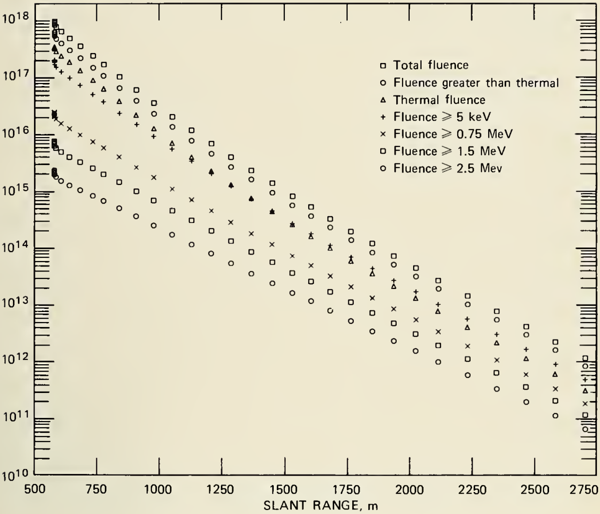

Fig. 13 Hiroshima neutron slant-range-squared (R^2) fluence.

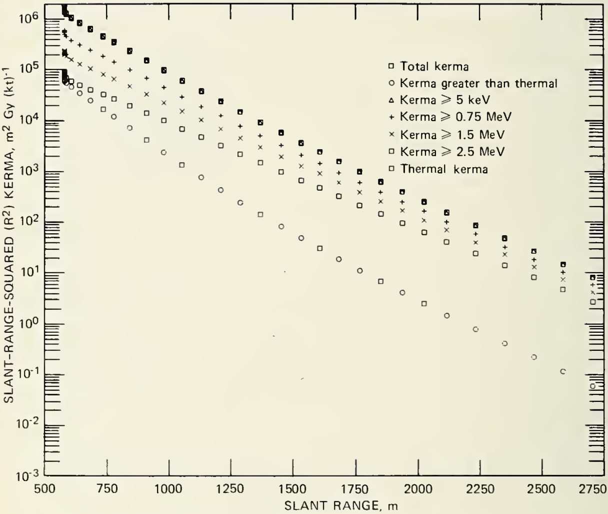

Fig. 14 Hiroshima neutron slant-range-squared (R^2) free-in-air tissue kerma.

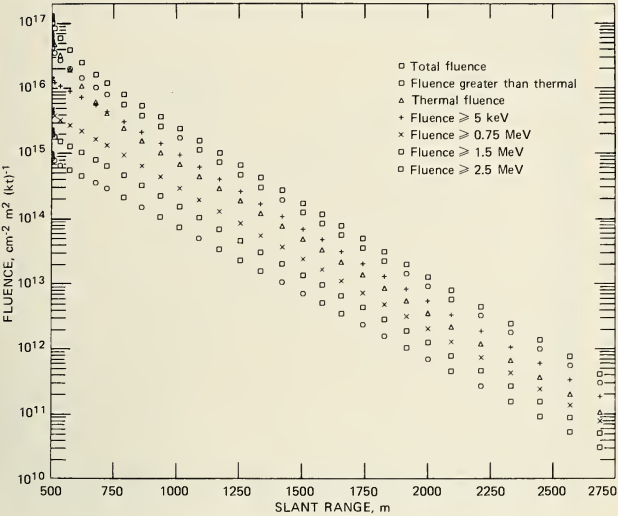

Fig. 15 Nagasaki neutron slant-range-squared (R^2) fluence.

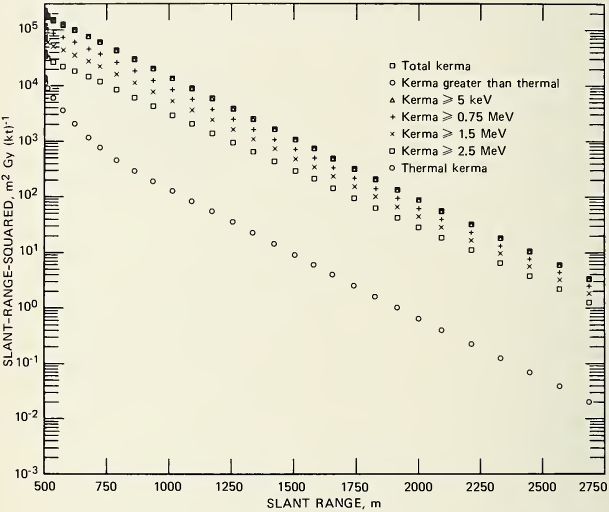

Fig. 16 Nagasaki neutron slant-range-squared (R^2) free-in-air tissue kerma.

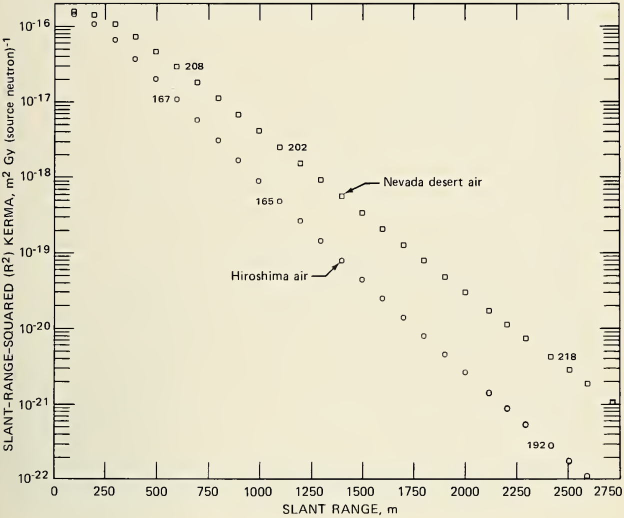

Fig. 17 Hiroshima slant-range-squared (R^2) neutron free-in-air tissue kerma in infinite air. The three-digit numbers next to some symbols represent the approximate relaxation lengths at those points.

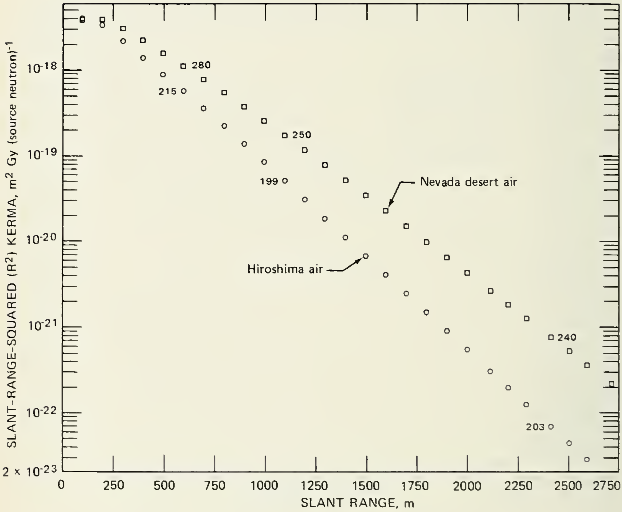

Fig. 18 Nagasaki slant-range-squared (R^2) neutron free-in-air tissue kerma in infinite air. Numbers next to some symbols represent the approximate relaxation lengths at those points.

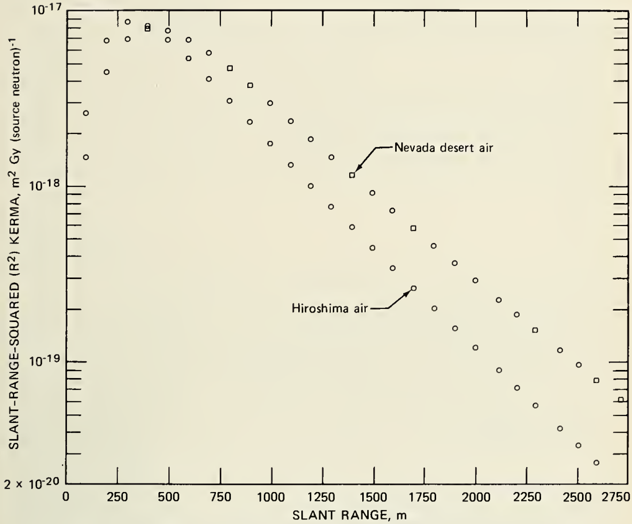

Fig. 19 Hiroshima slant-range-squared (R^2) secondary gamma free-in-air tissue kerma in infinite air.

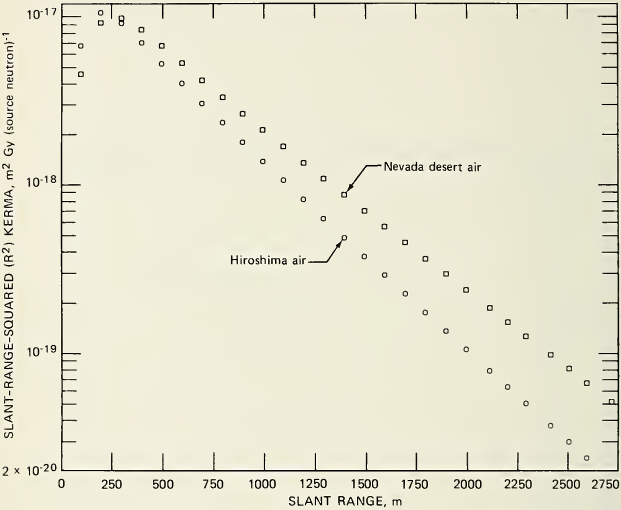

Fig. 20 Nagasaki slant-range-squared (R^2) secondary gamma free-in-air tissue kerma in infinite air.

tion, and gamma-ray production sensitivity. Before acceptance of any reevaluation of the dosimetric effects of the Hiroshima and Nagasaki weapons bursts, the previous calculations should be repeated with angular-dependent weapon leakage spectra and representative soil. For acceptance of the calculations by all personnel who might use the results, benchmark calculations must be made on several Nevada Test Site shots and the Ichiban, BREN, and Burlington AEC Plant experiments.

ACKNOWLEDGMENT

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DISCUSSION

Auxier: The ray effects have plagued me for a couple of years, since I first heard about them, and you specifically emphasized them for Fat Man. Picture a family of neutrons leaving the core of Fat Man. The dimensions are classified, but picture about 2 ft of high explosive, with about 20% of the atoms being hydrogen. That is more hydrogen that those neutrons will encounter out to 1000 m. Why is it that, as soon as they get outside the steel case, they are all engulfed in the air and make rays? That is the part that I don't understand.

Pace: The term "ray effects" refers to an anomaly that usually occurs with the use of the two-dimensional discrete-ordinates codes. For this effect to occur, the following three conditions must be met: (1) the sources and detectors are small compared with the total geometry, (2) the scattering mean free path is large compared with the space mesh used in the code, and (3) the angular mesh is such that it cannot "see" portions of the space mesh used in the code. If any one is not met, there will be no ray effects. None of these conditions is met when calculations are made through the weapon; in addition, the weapon calculations are usually made with Monte Carlo techniques. Outside the weapon, however, all three conditions exist. Two methods used by the shielding community to mitigate ray effects are the first-collision source method and the high-order quadrature method. The first-collision source method spreads the source throughout the total geometry and hence negates condition (1). The high-order quadrature method, together with the first-collision source method, negates conditions (1) and (3). Therefore the first-collision source method is used to mitigate the ray effects of the prompt neutrons and gamma rays, and the high-order angular quadrature is used to mitigate the ray effects of the secondary gamma rays produced by neutron capture in the air near the weapons. Would Dave Bartine like to add anything since he was involved in this?

Bartine: One general comment in regard to air-over-ground transport is that we have been doing calculations for a long time for the Defense Nuclear Agency, and, in general, in the last five years or so and when experimental measurements are available, we usually get agreement within 20 to 30%. If you asked me generically how well I expect our calculation results to agree with an experimental measurement, I would say within 20%. Otherwise we would look for an error in the calculation or probably in the experiment.

W. H. Scott: Regarding the accuracy of the Defence Research Establishment, Ottawa (DREO) and the Army Pulse Radiation Division (APRD) measurements that Paul Whalen was discussing, I got the impression from the comparison of measurement and calculation that in certain ranges there were some problems but that at 1100 m the experimental and the calculational energy spectra agreed surprisingly well, considering the problems in close. This may be due to experimental bias on those measurements. I don't know whether Paul did similar calculations at all the ranges for which data are available, since he showed only one range.

Delayed Radiation at Hiroshima and Nagasaki

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Science Applications, Inc., La Jolla, California

ABSTRACT

The delayed gamma-ray radiation from the decay of fission products in the fireball accounts for 40 to 60% of the total gamma-ray dose at Hiroshima and Nagasaki. During several aboveground nuclear tests in Nevada and the Pacific area, time-dependent measurements of the gamma-ray dose rates were made for a variety of yields, heights of burst, and ranges. Early efforts by Malik and Loewe fitted these data with simple physical models and adjustment factors.

Research funded by the Defense Nuclear Agency updated the NUIDEA computer model of nuclear effects so that the factors that govern the delayed dose were modeled from first principles. The dose rate is calculated by modeling the transport of the gamma rays through the expanding shock wave, density gradients, and rising fireball. The energy and time-dependent gamma-ray source is a function of fissioning isotope and is derived from ENDF-B-IV fission-product data files. Good comparisons between this model and the variety of time-dependent measurements at different ranges, yields, and heights of burst give confidence in NUIDEA and allow its use to establish the dose-vs.-range relationship for delayed gamma rays at Hiroshima and Nagasaki.

Noticeable differences, however, do exist between the measurements and the model at the largest ranges and for times between 0.1 and 1.5 sec when NUIDEA predicts a lower dose rate. An uncertainty study of possible causes indicates that the low-density fireball will delay the capture of thermal neutrons in the vicinity of the fireball. At longer ranges these late, high-energy air-capture gamma rays increase the gamma-ray dose rate as seen in the measurements. This effect is not at present modeled so that, at ranges of 2 km or larger, it is difficult to separate the measured air-capture gamma-ray dose from the delayed gamma-ray dose. Although further study will be required for verification, this extra dose appears to be normally included in the discrete ordinates transport (DOT) calculation of free-in-air secondary gamma rays. The best present estimate of total gamma-ray dose is obtained by adding the initial gamma rays calculated with the DOT code to the delayed dose from the NUIDEA model. These estimates, as predicted by Kerr, show that the total free-in-air gamma-ray doses at low doses are larger at Hiroshima and smaller at Nagasaki than those given by the tentative 1965 dose (T65D).

The delayed gamma-ray radiation from the decay of fission products in the fireball accounted for 40 to 60% of the total gamma-ray dose at Hiroshima and Nagasaki (Kerr, 1981). This dose was received in the first 20 sec after the burst, before the rising fireball carried the fission products away from the ground. The time dependence of the delayed gamma-ray dose is complicated by the fission-product decay rate, the reduction by the air shock in the amount of air between the source and locations on the ground, and, finally, the rising fireball. During several aboveground nuclear tests in Nevada and in the Pacific area, time-dependent measurements of the gamma-ray dose rate were made for a variety of yields, heights of burst, and ranges. Early efforts by Malik (1954) and by Loewe et al. (1966a, 1966b) fitted these data with physical models and adjustment factors.

In research funded by the Defense Nuclear Agency (DNA), we examined several existing delayed-radiation models and compared them with the time-dependent nuclear test data. The model that incorporates the most-detailed hydrodynamic and fireball-rise model is the NUIDEA code (Straker and Huszar, 1976), which includes the low-altitude multiple burst (LAMB) model (Needham and Wittwer, 1975) for scaling heights of burst and yields. We have found that comparisons of NUIDEA with the time-dependent test data are improved when the source of fission-product gamma rays is updated to include the fractions of original fissioning isotopes and the time- and energy-dependent decay rates. We obtained this isotope-, time-, and energy-dependent source of gamma rays from the work of LaBauve et al. (1978) at Los Alamos Scientific Laboratory (LASL), who had processed the ENDF/B-IV fission-product decay data file with the CINDER-10 code.

Good comparison with this model and the time-dependent nuclear test data gives confidence in NUIDEA and allows its use to establish the dose-vs.-range relationship at Hiroshima and Nagasaki. Noticeable differences, however, do exist between the weapons test measurements and the NUIDEA model at larger ranges and for times from 0.2 to 1.5 sec, where NUIDEA predicts a lower dose rate. This discrepancy suggests the existence of some high-energy early-time gamma-ray decays that are not at present in the ENDF/B-IV fission-product decay data file, and it contributes to the uncertainty of our model.

Our current estimates of the Hiroshima and Nagasaki delayed fission-product doses are derived directly from the NUIDEA model and include the Little Boy and Fat Man fission isotope fractions. Because no additional doses from high-energy gamma rays not in the present ENDF/B-IV data set have been added, the predicted fission-product doses at 2-km range are probably low. Table 1 presents these estimates, including probable upper

TABLE 1

Estimates of Hiroshima and Nagasaki Delayed Fission-Product Dose as Generated by the NUIDEA Model and Our Estimates of Upper and Lower Uncertainty Bounds

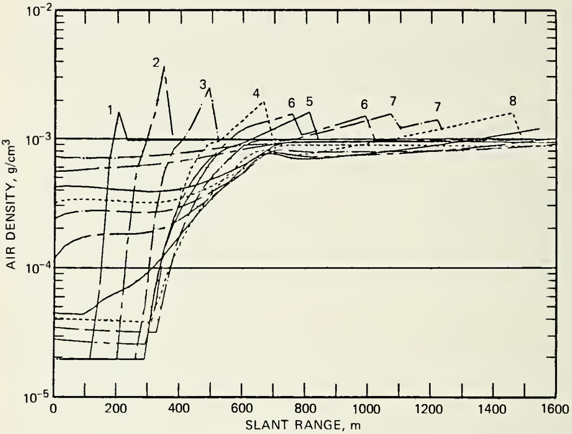
	Delayed fission-product dose, rads					
	At Hiroshima			At Nagasaki		
Ground distance range, m	NUIDEA model	Upper bound	Lower bound	NUIDEA model	Upper bound	Lower bound
100	4.9×10^{3}	6.4×10^{3}	3.9×10^{3}	1.6×10^{4}	2.1×10^{4}	1.3×10^{4}
300	3.0×10^{3}	3.9×10^{3}	2.4×10^{3}	9.5×10^{3}	1.2×10^{4}	7.6×10^{3}
600	9.5×10^{2}	1.2×10^{3}	7.6×10^{2}	2.5×10^{3}	3.3×10^{3}	2.0×10^{3}
1000	1.3×10^{2}	2.0×10^{2}	1.0×10^{2}	3.0×10^{2}	4.5×10^{2}	2.4×10^{2}
1500	1.3×10^{1}	2.3×10^{1}	1.1×10^{1}	2.5×10^{1}	4.4×10^{1}	2.1×10^{1}
2000	1.7×10^{0}	3.4×10^{0}	1.5×10^{0}	3.1×10^{0}	6.2×10^{0}	2.8×10^{0}

and lower bounds that represent our present concept of the accuracy of the model.

THE LAMB MODEL

The delayed gamma-ray radiation is strongly affected by the hydrodynamics of the nuclear burst in air. Initially, the advancing shock wave sweeps air out of the path between the source and the receiver, enhancing the dose rate. Later the fireball rises, rapidly reducing the dose rate on the ground. These geometry changes are modeled for a wide variety of yields, ranges, and heights of burst by the LAMB code (Needham and Wittwer, 1975). The LAMB model developed by the Air Force Weapons Laboratory is a synthesis of the results of many detailed hydrodynamic calculations and generates a fully three-dimensional description of the waveform following one or several nuclear bursts. The basis of the model is a one-dimensional 1-kt sea-level hydrodynamic calculation that provides the pressure, density, and particle velocity at any point behind the shock wave. This one-dimensional shock model is matched to a flat-bottomed exponential-well fireball model, a two-dimensional representation of the shock reflection from the ground, and the fireball-rise dynamics. Standard cube-root scaling and modified Sachs atmospheric scaling are used to calculate the shock parameters over a wide range of yields and altitudes.

Figure 1 shows the time evolution of the air-density profile generated by the LAMB model for a 71-kt burst at a 457.2-m height of burst. At



Curve	Time, sec	Curve	Time, sec
1	0.05	5	0.945
2	0.15	6	1.288
3	0.337	7	1.724
4	0.626	8	2.304

Fig. 1 Air-density-vs.-slant-range relationship modeled by the LAMB module of the NUIDEA code for Operation Plumbbob shot Hood, 71 kt at a 457.2-m height of burst.

times later than 1 sec, the ground-reflected shock is seen as a second density peak. The gamma-ray attenuation is calculated in the NUIDEA code by integrating these density profiles for the total thickness of the air to any desired receiver. The gamma-ray transport is then determined by rho-r scaling. This approximation was validated by demonstrating that one-dimensional gamma-ray transport calculations through the actual density profiles shown in Fig. 1 differed from rho-r scaling by <2%.

The energy, time, and isotope dependence of the fission-product gamma source was found to be important for correct comparison with the time-dependent measurements. Previous work, such as that of Loewe et al. (1966b) or of Huszar, Woolson, and Straker (1976) with air-transported radiation (ATR) dose, nearly always used a single gamma-ray energy spectrum independent either of time or of the weapon fissioning isotope. Usually this was the ^{235}U Fisher and Engles (1964) spectrum measured at

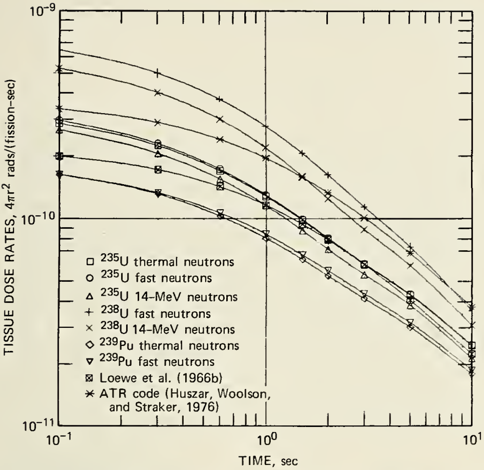


Fig. 2 Time-dependent fission-product sources: seven ENDF/B-IV time-dependent source spectra and two Fisher and Engles (1964) spectra with different normalizations folded with the tissue-dose response and plotted from 0.1 to 10 sec. The Fisher and Engles spectra with two normalizations are marked Loewe et al. (1966b) and ATR in the legend.

1.5 sec, which has an average gamma-ray energy of 1.0 MeV. The fissioning isotope is especially important because there are significant gamma-ray intensity differences among the fission products of ^{235}U, ^{238}U, and ^{239}Pu.

A fission-product-decay energy data file processed from ENDF/B-IV data into 20 gamma-ray energy groups was obtained from R. J. LaBauve and T. R. England of LASL (LaBauve et al., 1978) for ^{235}U, ^{238}U, and ^{239}Pu irradiated in 10^{-4} sec with thermal, fast, or 14-MeV neutron flux. Figure 2 shows the tissue rads of the source energy spectra from the three isotopes as a function of time. Thermal, fast, and 14-MeV irradiations are shown since they were available from the LASL data. These results are compared with two normalizations of the Fisher and Engles spectrum and the time dependence used in earlier delayed-radiation studies (labeled ATR) (Huszar, Woolson, and Straker, 1976) and Loewe et al. (1966b) on Fig. 2. The energy of the irradiating neutrons is seen not to be important, but the isotope type makes a major difference, with ^{238}U giving the highest, ^{235}U the middle, and ^{239}Pu the lowest dose rate. The ATR curve assumes an energy spectrum independent of time and isotope but with a time dependence of

$$\dot{D}(t) = \frac{0.8}{1 + 0.87t}$$

where $\dot{D}$ is the dose rate and t is the time in seconds. The curve labeled Loewe is from an earlier study in which Loewe et al. (1966b) noted that comparison with the Nevada test data was improved by multiplying the Fisher and Engles (1964) spectrum by 0.6. Figure 2 also shows that the Loewe model is close to the ^{235}U data at the important times after 1.0 sec. The Loewe values would also agree well with those for devices such as Fat Man which contain a mixture of ^{239}Pu and ^{238}U. Figure 3 shows a comparison of the fission-product gamma-ray intensity of ^{235}U as modeled from ENDF/B-IV data and measured by Dickens et al. (1980) of Oak Ridge National Laboratory (ORNL). The ordinate is given as the product of the source energy rate and the time (to conserve cycles of log paper).

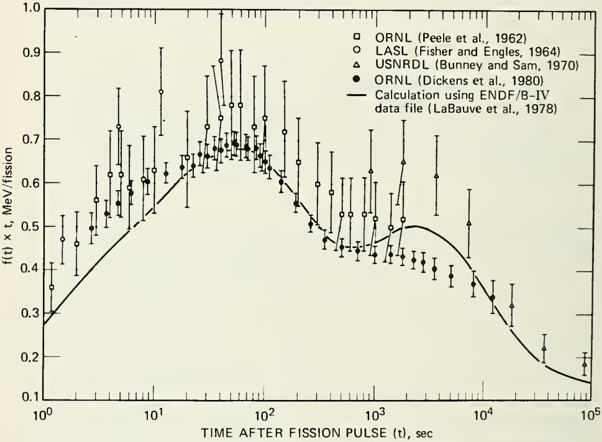


Fig. 3 Comparison of the calculated decay energy rate from ENDF/B-IV fission-product source with J. K. Dickens's recent measurements and those of other investigators for thermal neutron fission of ^{235}U as a function of time. The abscissa, t, is the time after a pulse of fission. The ordinate is a quantity derived by obtaining f(t) and then multiplying it by t. The units are a contraction of (sec · MeV · sec^{-1}/fission).

At the earliest experimental time, 2.8 sec, the ENDF/B-IV value is 80% of the experimental value. Therefore the ENDF/B-IV data appear to be somewhat low at 2.8 sec, and their accuracy at earlier times is not known.

The average energy of the ENDF/B-IV ^{235}U source is initially 0.5 MeV and increases to 1.0 MeV at 10 sec. Therefore the transport of this source through air will change with time. Figures 4 to 6 compare the air-transported dose in tissue for each of the three isotopes with the Fisher and Engles (1964) spectrum transported through the same amount of air. Results are shown for nine specified times from 0.1 to 10.0 sec, plotted as a function of air thickness in units of grams per square centimeter. Results are labeled "percent difference from ATR" to emphasize that the plots show the change in tissue dose from the Fisher and Engles source as a result of using the LASL ENDF/B-IV data. Figure 4 shows that, for the important times before 5 sec and the important ranges (100 to 200 g/cm^2 of air), the ^{235}U values are about 40% lower than those for the

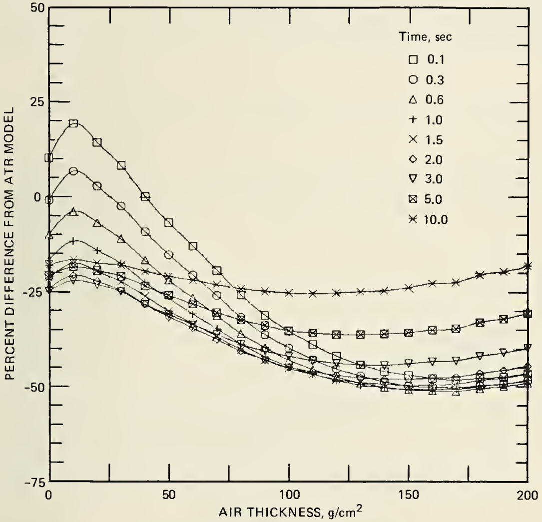


Fig. 4 Comparison of the air-transported tissue dose from the ^{239}U fast-fission ENDF/B-IV source with the ATR [Fisher and Engles (1964)] source at nine specified times from 0.1 to 10.0 sec as a function of air thickness.

Fisher and Engles dose. Apparently this explains the 0.6 normalization required by Loewe et al. (1966b) to best fit the test data. Figure 5 presents similar data for ^{239}Pu, which shows that the ENDF/B-IV data are 65% below the Fisher and Engles doses; Fig. 6 shows that the ^{238}U dose is either higher or comparable. The large increase in the ^{238}U dose at close ranges and early times results from the very soft ^{238}U ENDF/B-IV spectrum. Since these low-energy photons are well shielded by air, they usually are not important at ranges of interest with regard to weapons.

These source data were then incorporated into both the NUIDEA and ATR codes and compared with time-dependent dose-rate data from aboveground nuclear tests.

COMPARISON WITH TEST DATA

Time-dependent dose-rate measurements were made in many aboveground nuclear tests both in Nevada and in the Pacific area. The experimental values have been compared with various models, most notably by Malik (1954) and by Loewe et al. (1966a). Here we present comparisons with time-dependent data from three tests in the Operation

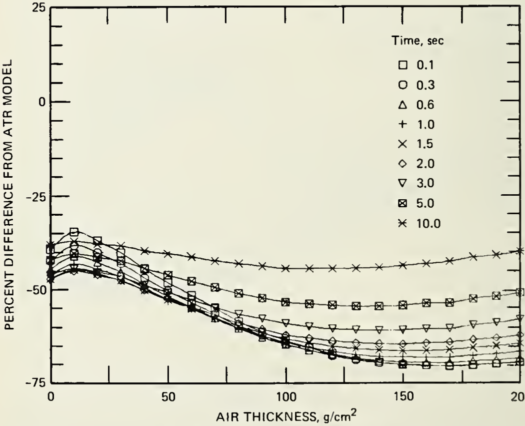


Fig. 5 Comparison of the air-transported tissue dose from the ^{239}Pu fast-fission ENDF/B-IV source with the ATR [Fisher and Engles (1964)] source at nine specified times from 0.1 to 10.0 sec as a function of air thickness.

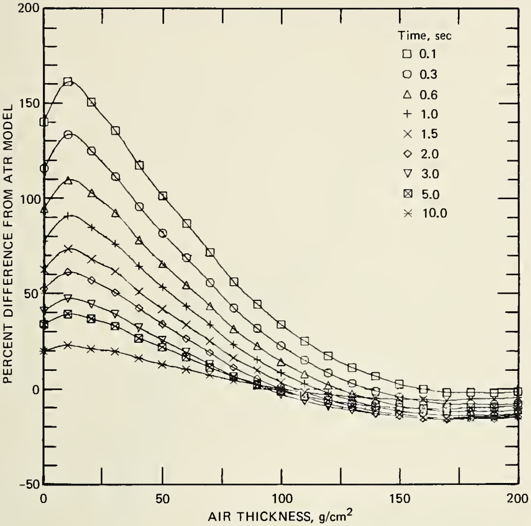


Fig. 6 **Comparison of the air-transported tissue dose from the ^{238}U fast-fission ENDF/B-IV source with the ATR [Fisher and Engles (1964)] source at nine specified times from 0.1 to 10.0 sec as a function of air thickness.**

Plumbbob series in Nevada in 1962. The shots, Hood, Wilson, and Owens, each had a different fraction of fissioning isotopes; this tests the importance of the ENDF/B-IV source data. Figure 7 compares four calculation models with the experimental measurement at a 1371-m ground range from shot Hood, a 71-kt yield with a burst height of 457 m, and an air density of 0.994 kg/m^3. The experimental data (triangles) include the early dose rate from the capture of thermal neutrons by nitrogen in the air. This part of the dose is normally calculated by the discrete-ordinates transport (DOT) code (Rhoades and Mynatt, 1973) as part of the secondary gamma-ray dose and therefore is not included in any of our models of the delayed radiation. The peak in experimental dose rate at 3 sec occurs when the shock front passes the detector at a 1371-m range. This is the time when the amount of air between the source and the detector is the least. The minimum in the dose rate at 1.8 sec is caused by the ground-reflected air shock moving additional air between the source and

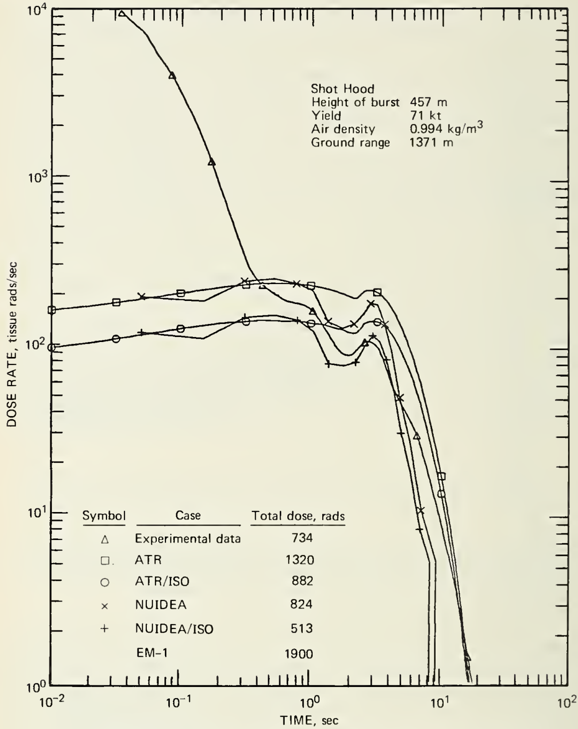


Fig. 7 Comparison of several fission-product models with the time-dependent dose-rate measurement for Operation Plumbbob shot Hood at ground range of 1371 m.

detector. Two curves for the NUIDEA code are shown: the upper curve, labeled NUIDEA, is for the previous version of the code with the Fisher and Engles source, and the lower curve, labeled NUIDEA/ISO, is for the same calculation with the ENDF/B-IV source. The ATR and ATR/ISO curves are the Fisher and Engles and the ENDF/B-IV versions of ATR, respectively. Qualitatively the NUIDEA/ISO model agrees in all important structures with the experiment, although at late times the experimental curve remains higher, which indicates that the fireball may have risen more slowly than that modeled in LAMB.

The total fission-product gamma-ray dose is listed in Fig. 7 for each model and also for the DNA's *Effects Manual 1* (EM-1) (Defense Nuclear Agency, 1972). The total dose for the experiment was determined by integrating under the entire curve and subtracting out the capture gamma-ray component. Considerable uncertainty is introduced here because the crossover from capture gamma-ray to fission-product dose is not well defined in the experimental data. We fitted the early capture dose rates by least squares with an exponential and, in the crossover regime, assumed that the difference between the fit and the data was fission-product dose. Because of these uncertainties, the integrations of the experimental values are accurate only to 20%.

Figures 8 and 9 show similar comparisons for Operation Plumbbob shots Wilson and Owens at ranges near 1 km. As in the case of shot Hood, the NUIDEA/ISO model in these cases is qualitatively similar to the experiment, giving a curve that agrees at the shock-arrival peak, and is a little low at other times. The integrated dose values are about 25% lower than the measured data. Similar comparisons were obtained in many shots at ranges of about 1 km.

Figure 10 shows the comparison for shot Hood at a range of 2779 m, which is representative of many more comparisons at these longer ranges. Here the shock-arrival peak is smoothed out by the fireball rise. At times after shock arrival, the NUIDEA/ISO model results agree well with the test data, but at times between 0.4 and 2.0 sec they are considerably lower; this indicates that something important is missing from the model. The early-time difference occurs in nearly all our large-range comparisons and also in the previous models by Malik and Loewe. Table 2 shows total-dose comparisons for Plumbbob shots Hood, Wilson, and Owens for a variety of ranges. The percent differences show that results from NUIDEA with the ENDF/B-IV source are generally low by 10 to 60%.

UNCERTAINTY INVESTIGATIONS

To determine the source of these differences, we studied many of the approximations in the model to identify any that might show underestimation at long ranges and early times. A major unknown is the actual location of the fission products in the fireball. NUIDEA assumes that all fission products are located at a point at the center of the fireball. Of course, this approximation makes calculations much simpler, but it is also quite good, as shown by our comparison with ANISN calculations (Engle, 1966) of a variety of possible source locations. In fact, it usually overestimates

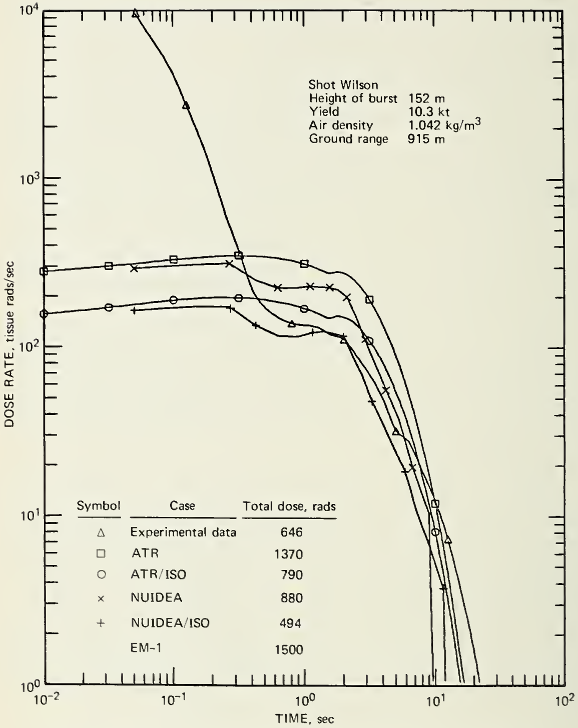


Fig. 8 Comparison of several fission-product models with the time-dependent dose-rate measurements for Operation Plumbbob shot Wilson at ground range of 915 m.

the dose by about 10% because, for other distributions of fission products in the fireball, many gamma rays exit at oblique angles and thus must penetrate more air. Radial distributions in the fireball were investigated by comparing ANISN calculations of actual air-density profiles from Fig. 1 with calculations using a variety of source-distribution assumptions. The square-well fireball model was also tested by allowing the fireball to be 10% larger, filled out with additional air, and having the fission products

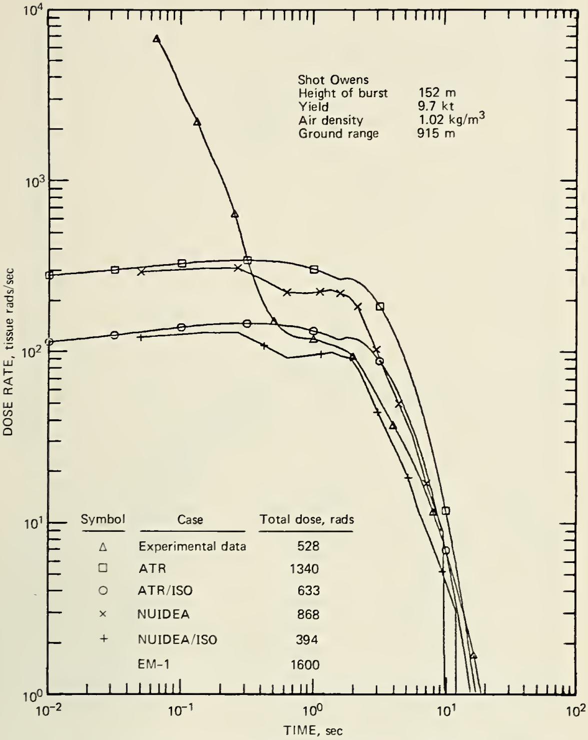


Fig. 9 Comparison of several fission-product models with the time-dependent dose-rate measurements for Operation Plumbbob shot Owens at ground range 915 m.

out to the edge of this larger fireball. Even in this case the dose was not larger than the NUIDEA assumptions. Vertical movement of the fission products was tested by moving the single point to the top and bottom of the fireball in NUIDEA. Again, no significant increase was seen.

Another possible explanation was investigated and found untenable: that thermal neutrons could make several passes through the hot, low-

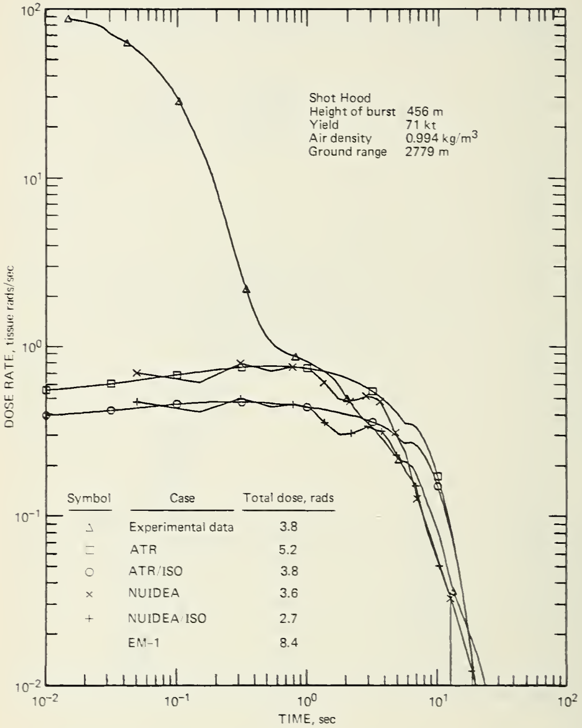


Fig. 10 Comparison of several fission-product models with the time-dependent dose-rate measurements for Operation Plumbbob shot Hood at ground range 2779 m.

density fireball, thus delaying their eventual capture. This could cause air-capture gamma rays to be generated much later than the 0.1-sec capture falloff in an undistributed atmosphere. This possibility was tested by comparing two time-dependent Monte Carlo infinite-air calculations, one of which had a 400-m-radius hole in the center of the air. The hole did increase the time of capture from 0.1 sec to 0.3 sec, but no gamma rays

TABLE 2

Difference Between NUIDEA/ISO Model Results and Estimates of the Fission-Product Dose Measured for Three Nevada Tests

Ground distance range, m	Fission-product dose, rads		Difference, %
	NUIDEA/ISO	Experiment	
Shot Hood			
915	4430	4430	0
1371	513	734	−30
2284	13	23	−43
2779	2.7	3.8	−29
3272	0.60	0.78	−23
Shot Wilson			
457	7.8×10^3	1.5×10^4	−48
915	494	646	−23
1370	49	57	−14
2285	1.1	1.5	−27
Shot Owens			
457	5.9×10^3	1.7×10^4	−65
915	394	528	−25
1370	41	50	−18
1829	5.5	7.2	−24
2285	1.0	1.4	−29
2779	0.19	0.22	−14

were generated out to 1.5 sec, where the large-range test data are still well above the NUIDEA/ISO model results.

Our final conclusion on the differences between our model and the test data is that there must be additional high-energy early-time gamma rays in the fission-product source which are not included in the ENDF/B-IV data set. In fact, LaBauve, England, and George (1981) have indicated in a recent LANL report that "calculated gamma-ray decay energies are relatively high for early cooling times and small gamma-ray energies, and they are low for early cooling times and large gamma-ray energies." They also give time-dependent fits to experimentally determined energy spectra from the measurements of Dickens et al. (1980). These spectra were measured at 2 sec and have an average gamma-ray energy of 0.95 MeV. The LANL investigators expect that these fits could be extrapolated back to 0.02 sec and would provide the best state-of-the-art determinations available to date. Our next step will be to try these new spectra, which are available only for ^{235}U and ^{239}Pu, in the NUIDEA model, to see if they will improve our comparisons with the test data.

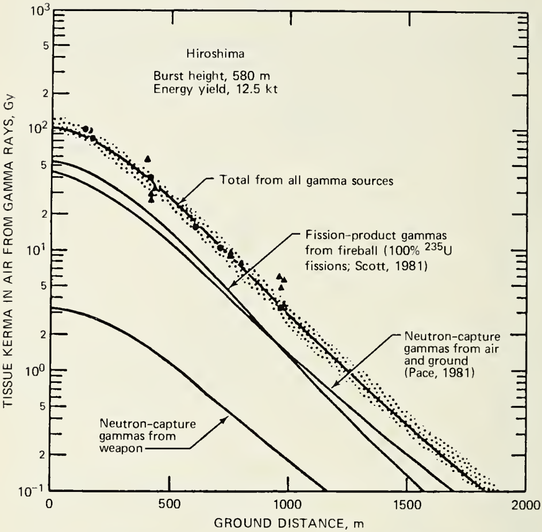


Fig. 11 Total gamma-ray dose at Hiroshima vs. range, as calculated by Pace (1981) and by this author, including the uncertainty (shaded area) in the total dose due to the uncertainty in the fission-product dose. ▲, Kyoto University (Ichikawa, Higashimura, and Sidei, 1966). ●, Japanese National Institute of Radiological Sciences (JNIRS) (Hashishume et al., 1967).

CONCLUSIONS FOR HIROSHIMA AND NAGASAKI

As described in the introductory section, our present estimates of the Hiroshima and Nagasaki delayed fission-product doses are determined directly from our NUIDEA model for the isotope fractions of Little Boy and Fat Man. Since we have not yet included any additional high-energy gamma rays not in the ENDF/B-IV source data, our doses at 2 km are probably low. These doses plus upper and lower uncertainties are shown in Table 1. Figures 11 and 12 show that our doses added to Pace's secondary gamma-ray calculation (Kerr, paper in this volume) give a total gamma-ray dose vs. range for Hiroshima and Nagasaki, respectively. The uncertainty in the total dose due only to the fission-product dose is shown as the shaded area. Clearly, the total-dose uncertainty would be larger to reflect

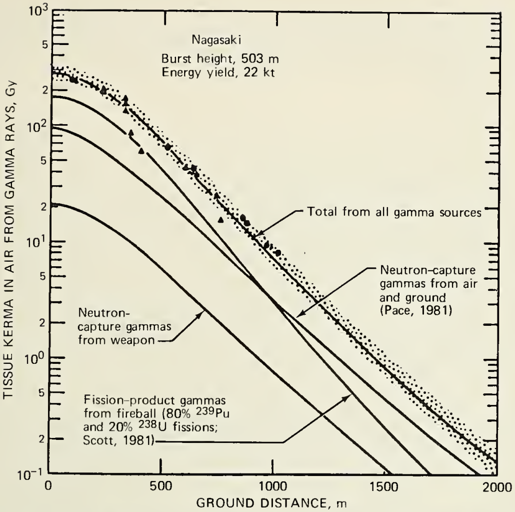


Fig. 12 Total gamma-ray dose at Nagasaki vs. range, as calculated by Pace (1981) and by this author, including the uncertainty (shaded area) in the total dose due to the uncertainty in the fission-product dose. ▲, Kyoto University (Ichikawa, Higashimura, and Sidei, 1966). ●, Japanese National Institute of Radiological Sciences (JNIRS) (Hashishume et al., 1967).

other uncertainties such as those in the source strength, the secondary gamma-ray calculation, and the atmospheric conditions.

The work described here documents our estimates of the fission-product doses at Hiroshima and Nagasaki. It also indicates, however, the need to examine the model with a more complete gamma-ray source such as that described in the recent LANL report (LaBauve, England, and George, 1981). Also, to divide the air-capture secondary gamma rays from the fission-product gamma rays more accurately, we recommend that further studies of the delayed dose from weapons tests include time-dependent Monte Carlo calculations of the capture gamma decay, possibly including the changing air geometry, if necessary, to predict the early-time dependence of the data.

In conclusion, we have presented estimates of the fission-product dose-vs.-range relationship at both Hiroshima and Nagasaki, including estimates of our uncertainties. Although further research should reduce the uncertainty at larger ranges, present estimates are sufficient to show that the present errors in the total dose due to the fission-product model are probably ±20%.

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DISCUSSION

Borg: You note a discrepancy between the gamma dose rate predicted by the NUIDEA computer model and actual measurements made at weapons tests for times between 0.1 and 1.5 sec, during which interval the field-measurement values exceed those calculated. Your source term for the calculations is the ENDF-B/IV fission-product data files, and you state that nowhere in there can you find a likely source for the "missing" gamma rays. Have you considered a gamma source derived from neutron-induced activities in weapons structural material or from weapons diagnostic apparatus or from tower components which were vaporized during the test detonations?

W. H. Scott: We have not done a detailed study of activation gamma rays from the Hiroshima and Nagasaki devices, and that would be a possible source. However, similar studies for Nevada tests have shown that activation gamma rays have lower intensities than the fission-product gamma rays, and that the half-lives are too long to explain our discrepancies between 0.1 and 1.5 sec.

Loewe: I would like to suggest that you compare results from your model with the data from the Ranger Fox event at the Nevada Test Site, which is alleged to be, and I think is generally accepted as, exceptionally high quality data. It is for total dose from an event with very strong similarity to the Nagasaki explosion. Do you plan to make a comparison in the total dose with those data by getting a secondary component and adding it onto your model?

W. H. Scott: Yes, you have shown in your *Nuclear Science and Engineering* paper excellent agreement with the total dose at Ranger Fox. I wish I could do that, but unfortunately we do not have a DOT calculation of the prompt and secondary gamma-ray components so that I could make that comparison exactly. If I scale my Nagasaki results to Ranger Fox as you have done at the range where you and the experiment have excellent agreement, mine would be some 10 rads lower.

Loewe: Out of how many?

W. H. Scott: I think you were saying something like 40 rads, and my model would underpredict that by some 10 rads.

Loewe: Ten out of forty.

W. H. Scott: Yes. However, I think it is very important to look at the full time dependence and try to understand what is going on because, if you don't match the full time behavior, you really can't seem to understand it.

Loewe: I agree. For understanding and developing the model, I couldn't agree with you more. For application to Hiroshima and Nagasaki, the Ranger Fox event happens to provide good data that have a strong resemblance to those from Nagasaki. But what does it all come down to? Your result is likely to be only 25% low, and you intend to raise your model estimate somewhat anyway, I believe.

W. H. Scott: To summarize, I am recommending my model even though I see that I am underpredicting at the long ranges. Bill Loewe is pointing out that his model does seem to get the Ranger Fox total dose better. However, I still maintain that it doesn't have the right time-dependent shape.

Kaul: We are recalculating the prompt and secondary gamma-ray dose for Ranger Fox from output data provided by LANL. Also, it must be noted that it is dangerous to assume that test devices have similar output simply because their exterior configurations or their high-explosive geometries are similar or even identical. In many cases significant changes were made to the fissile material or the tamper portions of the weapons as part of the ongoing experimental process. Thus it is absolutely mandatory that great care be taken to ensure that sources used in calculations of test-shot dosimetry be appropriate analogues for the devices in question.

W. H. Scott: Yes. I think what we are hearing is that, in all of this, it is very important to go back to the Nevada test data and to understand everything as well as you can. That is one series of experiments which will not be repeated; so it is imperative that you learn as much from it as you can while the people who can talk about it are still around.

Building-Transmission Factors

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ABSTRACT

Parametric representations (called the nine-parameter formula) of the measurements of the radiation transmission through Japanese house models at the BREN reactor and ^{60}Co experiments are used to correct the free-in-air (FIA) T65 dose values for building shielding in the built-up residential areas at Hiroshima and Nagasaki. The accuracy of transmission factors derived from the nine-parameter formula impact the accuracy of the final-exposure dose estimates in the same manner as the accuracy of weapon yield and FIA radiation transport. A preliminary investigation of the accuracy of these transmission factors, sponsored by the Defense Nuclear Agency, has focused primarily on the adequacy of the Bare Reactor Experiment, Nevada (BREN) radiation environments for producing transmission factor data relevant to the situations at Hiroshima and Nagasaki. In addition, the "radiation equivalency" of house models used at BREN to Japanese house models and the physical basis for the nine-parameter formula have been studied. This investigation has concluded that the average gamma-ray transmission factors based on the nine-parameter formula are probably too high by about a factor of 2. The average transmission factors from the application of the nine-parameter formula reported in 1968 were 0.316 for neutrons and 0.904 for gamma rays. However, the average gamma-ray transmission factor is now estimated to be close to 0.5. The large discrepancy between the nine-parameter formula and recent estimates results from the apparent failure to properly account for the large gamma-ray dose component caused by capture gamma rays produced in the house walls by the large neutron flux present at BREN. The neutron-to-gamma-ray flux ratio was much lower at Hiroshima and Nagasaki than at BREN or at the Hardtack weapons tests. The current estimate is based on scaling the ^{60}Co BREN data for air secondary gamma rays and fission-product gamma rays. Because of the lesser importance of the neutron dose, this study has not, at this point, attempted to quantify uncertainty in the neutron transmission factors, although significant questions about their accuracy can be raised. These questions concern the sensitivity of the transmission factors to differences in the spectrum and the hydrogen content of the walls.

Speakers at this symposium have discussed the procedures used to determine the radiation yield and output spectra of the devices used at

Hiroshima and Nagasaki. Others have discussed how these data are then used as source terms for the air-transport calculations to determine the free-in-air (FIA) radiation environments as a function of range from the detonation. The FIA calculations use a simplified geometry consisting of a flat-plane air–ground interface with no terrain or structures. In this paper the perturbation of this FIA environment caused by the presence of buildings in the vicinity of the subject location is discussed, and a companion paper by Dean Kaul (paper in this volume) discusses the transport of the perturbed in-house environment into the man and the effects of the man on the radiation dose at the local organ site of interest.

The effects of the buildings are treated in the T65D dosimetry system by the use of transmission factors (Auxier, 1977) which are applied directly to the FIA kerma to give the exposure kerma at the survivor's location. In this paper we show that the T65D transmission factors (TF) need reevaluation by describing, qualitatively, problems involved in a development of these transmission factors for the weapons used at Hiroshima and Nagasaki and by estimating the magnitudes of the errors involved in their use. Finally, we present a calculational procedure which can be used to model the effects of the buildings on the radiation environments and which can be applied to the Radiation Effects Research Foundation (RERF) survivor data bases (Beebe and Usagawa, 1968) and can be used in other studies.

TRANSMISSION FACTORS

The components of the total weapon-produced radiation environment in the air, in a house, and in man are depicted in Table 1. In free air the radiation environment from the bomb has four components: (1) the neutron fluence, (2) the secondary gamma-ray fluence from neutron capture and inelastic interactions in the air and in the ground, (3) the prompt gamma-ray fluence from gamma rays that were emitted in very short

TABLE 1

Bomb Radiation Environments

Free in air	Inside house	Organ sites in man
Neutrons	Neutrons	Neutrons
Air secondary gamma rays	Air secondary gamma rays	Air secondary gamma rays
Prompt gamma rays	Prompt gamma rays	Prompt gamma rays
Delayed gamma rays	Delayed gamma rays	Delayed gamma rays
	House secondary gamma rays	House secondary gamma rays
		Man secondary gamma rays

times from the bomb, and (4) the delayed gamma-ray fluence from the decay of fission products. When the neutron environment interacts with the house materials, secondary gamma rays, primarily from neutron capture, are produced. Thus, in the house (and nearby outside), there is an additional gamma-ray component from these house secondary gamma rays along with the incident FIA neutrons and gamma rays that have been attenuated by the house. When the house-attenuated neutrons interact in the man, another gamma-ray component at the organ site results from secondary gamma-ray production in the man. What started as a four-component radiation environment results in six separate environments at the local organ site. The two additional gamma-ray environments arise from secondary gamma-ray production in the house materials and in the man.

In a transmission-factor scheme applied to the FIA environment to account for house and man, one must pay careful attention to the treatment of these added secondary gamma-ray components. Two possible schemes for obtaining transmission factors are:

- METHOD 1

$$\text{Neutron TF} = \frac{\text{Neutron} + \text{house 2nd } \gamma + \text{man 2nd } \gamma \text{ doses}}{\text{FIA neutron kerma}}$$

$$\text{Gamma TF} = \frac{\text{Air 2nd } \gamma + \text{prompt } \gamma + \text{delayed } \gamma \text{ doses}}{\text{FIA gamma-ray kerma}}$$

- METHOD 2

$$\text{Neutron TF} = \frac{\text{Neutron dose}}{\text{FIA neutron kerma}}$$

Gamma TF

$$= \frac{\text{House 2nd } \gamma + \text{man 2nd } \gamma + \text{air 2nd } \gamma + \text{prompt } \gamma + \text{delayed } \gamma \text{ doses}}{\text{FIA gamma-ray kerma}}$$

where 2nd γ is the secondary gamma ray.

In the first method the secondary gamma-ray dose from the house and man and the neutron dose comprise the numerator, and the FIA neutron kerma is the denominator. This factor, applied directly to the FIA neutron environment, gives the total dose at the organ site from the incident neutrons. This scheme, however, does not separate the neutron and gamma-ray dose components and cannot be used if one is interested in determining the relative biological effectiveness (RBE) of the neutrons. It is also very difficult to produce transmission factors based on this scheme from experimental measurements in a mixed neutron and gamma-ray environment. These factors are usually produced by calculational results that clearly delineate the individual organ-dose components.

The second method accounts for the additional gamma-ray components in a transmission factor that is applied to the incident gamma-ray environment. This transmission factor is the ratio of the sum of neutron-induced gamma-ray dose and attenuated incident gamma-ray dose to the FIA gamma-ray kerma. This method has the advantage of separating the neutron and gamma-ray doses, but it has a major disadvantage because the gamma-ray transmission factor then depends on the neutron environment and the neutronics of the house materials. Since the relative magnitudes of the incident neutron and gamma-ray environments are a function of the weapon design and change as a function of range for any weapon, a single integral transmission factor independent of device or range will not provide accurate results. This transmission factor can, however, be determined experimentally. It is the ratio of the measured kerma inside the house (ignoring the man effect) to the measured FIA kerma at the same range unperturbed by the presence of the house.

T65D TRANSMISSION FACTORS

The T65D dosimetry system used measured transmission factors (Method 2) to account for house shielding (Auxier, 1977). Self-shielding effects in man were not treated in the initial dosimetry system. Thus the T65D system provides the exposure kerma at the subject location when transmission factors are applied to the FIA kerma.

To measure the neutron and gamma-ray structure-transmission factors for Hiroshima and Nagasaki, models of typical Japanese houses were produced and were exposed to several Nevada weapons tests, the Bare Reactor Experiment, Nevada (BREN) reactor, and the BREN ^{60}Co experiments (Auxier, 1977). The BREN experiments consisted of suspending a bare reactor or a ^{60}Co source in a tower at the Nevada Test Site at heights up to 1500 ft. To determine the radiation transmission at the tests and BREN experiments, neutron and gamma-ray detectors were placed at many locations within the house models and also at the same ground range, but at some distance away from the structures, to determine the FIA kerma. Table 2 contains the average transmission factors for single stand-alone houses measured at the weapons tests Plumbbob (Ritchie and Hurst, 1959) and Hardtack (Auxier et al., 1960) and at BREN (Cheka et al., 1965). The transmission factors in Table 2 were averaged over all locations within the house. The variations seen in the neutron transmission factor is reasonably consistent, but there is a large variation in the gamma-ray transmission factor among Plumbbob, Hardtack, and BREN.

TABLE 2

Average Single-House Transmission Factors

Event	Neutron	Gamma ray
Plumbbob	0.507 ± 0.11	0.769 ± 0.11
Hardtack	0.407 ± 0.09	0.952 ± 0.15
BREN reactor	0.515 ± 0.15	1.35 ± 0.08
BREN ^{60}Co		0.464 ± 0.18

The BREN ^{60}Co measurements did not involve a neutron environment, and the average is about half that in the other experiments in which neutrons were present. The variation in the gamma-ray measurements among Plumbbob, Hardtack, and BREN is due to the different relative neutron and gamma-ray environments at the locations of the houses. The neutron-to-gamma-ray kerma ratios for these events are listed in Table 3. The BREN reactor experiment had a large neutron-to-gamma-ray ratio compared with the weapons tests because of the absence of fission-product gamma rays. Note, however, the very small ratio for Hiroshima and Nagasaki devices based on the calculations of J. V. Pace and of W. H. Scott and presented at this conference. At both Nagasaki and Hiroshima, few neutrons were present; thus the level of house secondary gamma rays inside the houses was much lower than that at the weapons tests and BREN experiments.

TABLE 3

Ratios of Neutron-to-Gamma-Ray Kerma at 1000-m Ground Range

BREN reactor	1.37
Fission weapon (~10 kt)	~1.00
Nagasaki	0.01*
Hiroshima	0.10*

*Based on calculations of Pace, Knight, and Bartine (paper in this volume) and of W. H. Scott (paper in this volume).

The transmission factors used in the T65D system were derived from the BREN measurements (Auxier, 1977). During the BREN experiments several types of building clusters consisting of several house models in arrangements typical of Japanese residential areas were used in addition to single houses. These clusters provided the attenuation effects of nearby buildings on the exposure at survivor locations. Parametric formulas were developed to predict the transmission factors from the reactor neutron measurements, the reactor gamma-ray measurements, and the ^{60}Co measurement as a function of certain attributes of the exposure location (e.g., distance to nearest wall) (Cheka et al., 1965). The ^{60}Co transmission factors were used to account for the fission-product component missing in the BREN reactor experiment. These formulas, called the "nine-parameter formulas," were able to reproduce the experimental BREN measurements with good accuracy and precision.

The nine-parameter formula for the BREN neutrons was used to determine neutron transmission factors for the survivors on the basis of the parameter values pertinent to the survivor location and nearby configurations. The gamma-ray transmission factors for Nagasaki were composed of a mix of 45% of the reactor gamma-ray transmission factor and 55% of the ^{60}Co gamma-ray transmission factor. At Hiroshima the ratio was reversed; i.e., a mix of 55% of the reactor transmission factor and 45% of the ^{60}Co transmission factor was used. The mix of 45% reactor and 55% ^{60}Co transmission factors gave good agreement with the gamma measurements made at Operation Hardtack and was assumed to be appropriate for the Nagasaki weapon (Auxier, 1977). The 55% : 45% ratio for Hiroshima was assumed appropriate because of the additional neutron output from the Hiroshima device, which would cause a larger secondary gamma-ray component (Auxier, 1977). However, as we have noted, there were far more neutrons at Hardtack and BREN than at either Hiroshima or Nagasaki. Therefore the nine-parameter gamma-ray transmission factors are too large because of a large house capture gamma-ray component that was not present at Hiroshima or Nagasaki.

PRELIMINARY ESTIMATE OF GAMMA-RAY TRANSMISSION FACTORS

The BREN average gamma-ray transmission factors for a single house at Hiroshima and Nagasaki are given in Table 4. These numbers are based on the single-house average transmission factors from the BREN reactor and ^{60}Co experiments given in Table 2 and the 55% : 45% ratio for Hiroshima and the 45% : 55% ratio for Nagasaki. Milton and Shohoji (1968) gave average transmission factors for Hiroshima and Nagasaki which were derived from the application of the nine-parameter formula to the locations of the RERF data-base subjects. These values, also given in Table 4, are lower than the single-house averages because the surrounding buildings in residential areas also attenuate the radiation. The effect of the surrounding buildings on the transmission factor appears to be to change the single-house value by a power in the range between 2 and $\tfrac{3}{2}$. The ranges of values (labeled "Multiple-house model") are shown in Table 4. Note that, if the multiple-house transmission factor is the square of the single-house transmission factor, the surrounding structures provide

TABLE 4

Average Gamma-Ray Transmission Factors

	Hiroshima	**Nagasaki**
Single-house average (BREN)	0.95	0.87
Sample derived by nine-parameter formula (Milton and Shohoji, 1968)	0.90	0.81
Multiple-house model	0.90* to 0.93†	0.76 to 0.81

*0.90 = $(0.95)^2$. †0.93 = $(0.95)^{3/2}$.

the same amount of attenuation as the house containing the exposure location. This model of multiple-house effects will be used to reevaluate the average gamma-ray transmission factors at Hiroshima and Nagasaki on the basis of the BREN ^{60}Co measurements (the only gamma-ray transmission-factor measurements that were made with a pure gamma-ray field).

The BREN ^{60}Co fluence spectrum at the experimental houses is different from the spectrum of gamma rays that would be incident on the houses at Hiroshima and Nagasaki from fission-product gamma rays and air secondary gamma rays. To make an estimate appropriate for these environments, the transmission-factor measurements made at BREN will be scaled for the difference in attenuation due to the different spectra of these two gamma-ray components. The thicknesses of concrete to reduce the dose by 1/e for ^{60}Co gamma rays is 20 g/cm^2; for fission-product gamma rays, 31 g/cm^2; and for air secondary gamma rays, 44 g/cm^2. These thicknesses are based on one-dimensional discrete ordinates calculations and are appropriate for the transported spectra at a ground range of 1 km. The gamma-ray attenuation for concrete is probably not too different from that for Japanese house material (clay plaster and tile).

The average of all transmission factors for a single house for the BREN ^{60}Co measurements was 0.464 (Table 2). Thus the thickness of material to give this attenuation for a ^{60}Co gamma-ray spectrum at the 1-km ground range is

$$t = -20 \ln 0.464 = 15.36 \text{ g/cm}^2$$

The corresponding transmission factor for the fission-product gamma rays and the air secondary gamma rays is then

$$\text{TF} = \frac{1}{2}\left[\exp\left(-\frac{15.36}{31}\right) + \exp\left(-\frac{15.36}{44}\right)\right] = 0.66$$

for a single house unshielded by other structures. Then, if we apply the multiple-house model, the values for the transmission factors in the built-up areas in Japan are estimated to be between 0.43 and 0.54. The actual transmission factors at Hiroshima would be somewhat larger because of the larger neutron component.

One of us (Marcum, 1981) made the first estimate of gamma-ray transmission factors for Hiroshima and Nagasaki along this line of argument and found that the average of all BREN ^{60}Co transmission-factor measurements was 0.35. This average included all the multiple-house and single-house arrangements. If these ^{60}Co measurements are scaled up for a 50 : 50 ratio of fission-product gamma rays and air secondary gamma rays, the transmission factor becomes 0.50 (which was Marcum's estimate for Nagasaki). The transmission factor for Hiroshima was estimated to be 0.55 because of the neutron capture in the house walls. This earlier estimate is within the range that we have presented in this paper.

Other estimates (Marcum, 1981) of gamma-ray transmission factors are:

- **Dikewood (Davis et al., 1968)**

Hiroshima	$0.55^{+0.22}_{-0.13}$
Nagasaki	$0.48^{+0.23}_{-0.11}$

- **Science Applications, Inc., Adjoint One-Dimensional Calculations (Woolson, 1981)**

Hiroshima	0.56
Nagasaki	0.53

Although the Dikewood (Davis et al., 1968) estimates for gamma-ray transmissions are significantly different from those used in the T65D system for gamma rays, the estimates by Davis et al. for neutron transmission factors were not inconsistent with the nine-parameter formula. Based on the one-dimensional adjoint calculations made at Science Applications, Inc. (SAI), the gamma-ray transmission factors at Hiroshima and Nagasaki were estimated to be 0.56 and 0.53, respectively (Woolson, 1981).

We conclude, from this very preliminary investigation, that the nine-parameter-formula transmission factors for gamma rays are too large. This is based on qualitative physical arguments concerning the capture gamma-ray component in the house walls at BREN. The preceding estimates indicate that these previous average transmission factors are probably too large by nearly a factor of 2. This results in a bias in the gamma-ray dose which is larger than the reported uncertainties in the current free-in-air calculations, even including uncertainties resulting from the anisotropy of the source at Hiroshima.

Calculations are currently under way at SAI to refine the estimates of the gamma-ray transmission factors for Japan. Two-dimensional discrete-ordinate calculations with the discrete ordinate transport (DOT) code (Rhoades and Mynatt, 1973) for the BREN reactor and ^{60}Co experiments have been performed. These calculations are very similar to the types of calculations used to produce the FIA kerma estimates for the Hiroshima and Nagasaki weapons (Pace, Knight, and Bartine, paper in this volume). These calculations give the unperturbed air-over-ground transport environment in the vicinity of the house models that were used to make the transmission-factor measurements. Adjoint Monte Carlo calculations are currently being performed with the MORSE code (Straker, Scott, and Byrn, 1972) for detailed, three-dimensional models of the house configurations used in the BREN experiments. These calculations generate an energy- and angle-dependent response function that gives the perturbation in the environment caused by the presence of the house. This response function will then be folded with the FIA BREN environment calculations to give a calculational transmission factor that can be compared with the BREN measurements. This comparison of calculated and experimental data should validate the calculational procedures. The same adjoint house response function will then be folded with the FIA radiation environments computed for the Hiroshima and Nagasaki sources. This, then, will provide the transmission factors as a function of ground range for the two bombs. The model of the house used in these calculations is shown in Fig. 1. This is a mathematical-geometry model of house A, in which a large number of the measurements were made at BREN (Cheka et al., 1965) and for which data were obtained in both the Plumbbob (Ritchie and Hurst, 1959) and Hardtack (Auxier et al., 1960) experiments.

NEUTRON TRANSMISSION FACTORS

The measured transmission factors for neutrons at the Plumbbob, Hardtack, and BREN experiments appear to be consistent (Table 2). There is no apparent reason to doubt the accuracy of the neutron measurements at BREN. Two questions need further investigation, however, before we can conclude that the nine-parameter formula is adequate for dosimetry at Hiroshima and Nagasaki: (1) Were the BREN house models equivalent radiation analogs, for neutrons, of residential dwellings in Japan? and (2) Does the nine-parameter formula accurately account for building-cluster effects occurring in the built-up high-density areas?

The house models used at BREN were constructed of a cement–asbestos board called Transite (Johns-Manville Corporation), which purportedly was a radiation analog of Japanese house materials

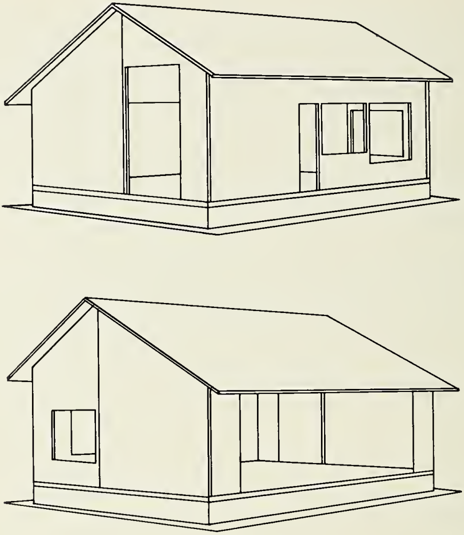

Fig. 1 Combinatorial-geometry model of house A.

(Auxier, 1977). The radiation equivalency of Transite was based on laboratory ^{60}Co gamma-ray and Po–Be neutron-source attenuation measurements which showed the same neutron-to-gamma-ray attenuation ratio as that obtained for Japanese house materials (Morgan, 1959). Gamma-ray attenuation, however, is mainly dependent on the mass penetration and equivalent atomic number of the material, and neutron attenuation is highly dependent on the hydrogen content. One of us (Woolson) has found that the wall mass penetration thickness used in the BREN houses was less than reported and has estimated that the hydrogen content of the BREN model walls was probably much less than that of the Japanese house walls in the high humidity of August weather. Current research will pursue these concerns to arrive at some quantification of their impact on neutron and gamma-ray transmission factors.

The incident neutron environment is more omnidirectional than the gamma rays; thus the neutron transmission factors have a greater dependence on multiple-building effects. The parameters and their functional dependence in the nine-parameter formula may not be sufficient to reproduce and predict, as accurately as claimed, the neutron transmission factors for Hiroshima and Nagasaki. This question is also being examined.

CALCULATION OF TRANSMISSION FACTORS FOR HIROSHIMA AND NAGASAKI

We have suggested a calculational method to reevaluate the effects of buildings on the radiation exposure to survivors. This method is being verified by comparing calculations for the BREN experiments with the measurements, as described above. Although the relative magnitudes of components of the environments for the BREN experiments were different from those for Hiroshima and Nagasaki, agreement between calculation and measurement (or understanding of the differences) for individual BREN environments will verify the calculational procedures for application to the Hiroshima and Nagasaki environments.

The calculational procedure maintains complete detail in the effects of the buildings as a function of range, e.g., spectral shifts in the FIA environment, orientation of the houses with respect to the burst, and location of the subject in the house. These calculational results can be used to revert back to the use of single integral "dose" transmission factors; however, more importantly, by providing the detailed radiation environment in the houses, the results can be used to calculate the radiation transport in the subjects. Thus the neutron and gamma-ray doses at critical organ locations can be obtained. Since great emphasis has been placed on using the Japanese data bases to study the RBE of neutrons and gamma rays, it is important that these dose components be accurately calculated in the correct ratio at local organ sites.

The calculational procedure we recommend has been developed and applied to similar problems in the areas of house and army-tank transmission-factor calculations. The procedure is embodied in a series of computer codes called VCS (Vehicle Code System) (Rhoades et al., 1973). VCS is composed of three codes, MORSE, VISA, and DRC. The well-known MORSE code (Straker, Scott, and Byrn, 1972) is a multigroup Monte Carlo radiation transport code particularly suited for adjoint coupled neutron secondary gamma-ray computations. VISA reads the appropriate FIA energy angular fluence from the DOT fluence tapes, and DRC folds the adjoint MORSE calculation with the VISA data to give the perturbed inside environment from the FIA environment.

The MORSE code is used to compute the perturbation of the FIA environment by the presence of the house structures with adjoint transport commencing at the exposure location. The Monte Carlo simulation is performed with a mathematical-geometry model of a typical building cluster containing about six neighboring houses in an arrangement typical of the

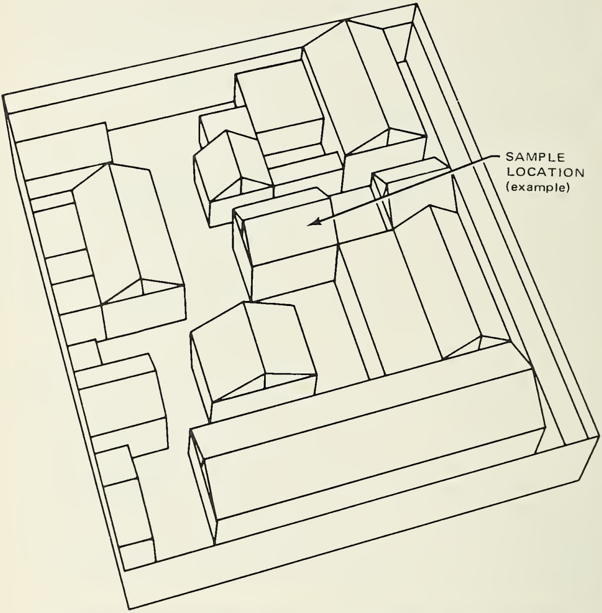

Fig. 2 Model for a building cluster for a VCS (Vehicle Code System) calculation.

built-up residential areas in Japan. An example of a building cluster used for similar calculations for small villages in Europe is shown in Fig. 2. The calculation provides the building transmission function,

$$T(E,\overline{\Omega} \rightarrow E',\overline{\Omega}')$$

which gives the energy angular fluence at the exposure location $\phi_e(E',\overline{\Omega}')$ consisting of attenuated neutron fluence, house capture gamma-ray fluence, and attenuated incident gamma-ray fluence per unit incident FIA energy angular-dependent fluence. Thus the exposure fluence $\phi_e(E',\overline{\Omega}')$ is given in terms of the FIA fluence $\phi_A(E,\overline{\Omega})$ by

$$\phi_e(E',\overline{\Omega}') = \int dE \int d\overline{\Omega}\ \phi_A(E,\overline{\Omega})\ T(E,\overline{\Omega} \rightarrow E',\overline{\Omega}')$$

The numerical integrations of this equation are done by DRC code, which takes the FIA DOT fluence $\phi_A(E,\overline{\Omega})$ and the MORSE calculation of the building effects $T(E,\overline{\Omega} \rightarrow E',\overline{\Omega}')$ and folds them as a function of range from the burst and orientation of the cluster with respect to the burst. The numerical integrations can be performed inexpensively for many cases, and much information can be gained from a few detailed transport calculations for the building cluster. Many more situations than were used in the BREN experiments to develop the previous models can be examined calculationally.

The results of these calculations can be used to develop models of transmission factors for application to the survivors in the RERF data bases (Beebe and Usagawa, 1968). The models would be constrained to use the available information for each subject, which is already present in the data base. This information includes the nine parameters used in the nine-parameter formula, the building mass on the line of sight from the bomb to the subject, and the coordinate location of the subject.

Since many calculations can be performed with simple numerical integrations, preliminary analysis would proceed by answering the following questions:

- What is the ground-range dependence of the transmission factors?
- What are the bounds of the variation of the transmission factors within a given dwelling?
- What are the sensitivities of the transmission factors to features of the dwellings (such as windows) and exposure location?
- How well does the parametric representation embodied in the nine-parameter formula reproduce the calculations (that is, do only the constants need changing, or are new formulas needed)?

From this preliminary study, additional investigations can be made to produce the models for the building effects and for the uncertainty analysis for application to the RERF data base.

TRANSMISSION FACTOR FOR WORKERS IN NAGASAKI MITSUBISHI STEEL AND ORDNANCE PLANTS

In the RERF data bases, a large fraction of the survivors in the 1250- to 1550-m ground range at Nagasaki were assigned the FIA dose with no shielding (Marcum, 1981). Milton and Shohoji (1968) indicate that 957 out of a total of 2229 survivors in this range were given the FIA dose. The normal percentage for other ranges at Hiroshima and Nagasaki is much lower.

Most of these 957 subjects were in the Mitsubishi steel and ordnance plants at the time of bomb detonation (Kerr, 1981). These plants were of steel-frame construction with cement–asbestos walls and corrugated-steel roofs. The plants contained much heavy machinery, and the floors were probably of thick load-bearing concrete.

The rationale for the FIA dose assignment was a series of measurements made with a radium gamma-ray source that showed very little attenuation by the cement–asbestos walls (Auxier, 1977). These experiments probably measured only direct-beam attenuation and did not account for the slant paths of the incident radiation from the bomb. Furthermore, the shielding effects of the machinery, floors, and other objects inside the plants were ignored.

Most of the risk data for Nagasaki derived from radiobiological analysis of survivor data bases show a pronounced "dip" in the risk curve in the vicinity of the dose assigned to the Mitsubishi workers. A reanalysis of the transmission factors for these subjects *may* result in more-consistent risk curves if the dose assignments are reduced because of reduced transmission factors (i.e., increased shielding).

We suggest a two-step program to investigate this problem. The first step is to calculate the transmission factors for the plant shell (walls and roofs) and floors. Available data in the U. S. Strategic Bombing Survey (USSBS) reports (1947a; 1947b), RERF data bases, and other sources on building construction will be used to produce models for the adjoint Monte Carlo radiation-transport calculations of the building transmission. These calculations will provide the maximum transmission (minimum shielding) to the survivor locations.

The next step is to account for the presence of machinery and other objects inside the plant which would significantly perturb the transmission factors for individual locations. Detailed calculations for each location would be too costly and impractical. However, a few detailed calculations for selected locations, which include nearby objects, will probably permit experienced radiation analysts to derive accurate transmission factors by synthesizing less-detailed transport data; that is, models using one-dimensional calculations, the solid angle intercepted by nearby objects, and other information can be developed for application to most subject locations in the data base and can be verified by the detailed results.

Ultimately, the estimated transmission factors may not show a large variation from case to case, and thus average transmission factors may suffice except for a few locations that may be either peculiar from the shielding viewpoint or of particular interest from the radiobiological viewpoint.

The results of this program might have significant impact on the current "conventional wisdom" about intercity differences in radiobiological effects. It is another important example of the need to pay great attention to the dosimetry before reliable conclusions can be drawn from the biological end points.

TRANSMISSION FACTORS FOR SURVIVORS IN CONCRETE BUILDINGS

The extraction of meaningful quantitative, dose-dependent early-effects information (e.g., dose for 5 to 10% mortality) from the available data bases has been extremely difficult. This difficulty stems from the imprecise locations (±200 m or more) and poor dosimetry for the individuals in the initial Armed Forces Institute of Pathology (AFIP) survey (Oughterson and Warren, 1956) but which does include excellent medical observations and data (blood counts, etc.). Later surveys have good locations and dosimetry but lack precise medical data because these were made years after the detonation. To combine the medical data from the AFIP with the dosimetry of the later surveys requires identification of specific individuals documented in *both* data bases. The amount of overlap between these data bases for the wood-frame dwellings and the outside-shielded categories (those for which the dose has been estimated) has been disappointingly low (Summers and Slosarik, 1980). It appears that the different groups of individuals concentrated on in the surveys resulted in the low overlap.

Other difficulties appear if one desires individual incidence rates (e.g., percent radiation mortality at specific dose level). The radiation injury must be uncomplicated by other injury mechanisms (e.g., blast and thermal); this eliminates, for example, individuals in the open because of complications from thermal burns. Moreover, only grouped data (two or more individuals in a single group identified and accounted for by one or more survivors) can be used for incidence rates. Isolated individual data cannot be used, because the individuals suffering early mortality cannot be accounted for.

One group of individuals that overcame all but one of the above difficulties (dosimetry) were located in concrete buildings. This data base has the following attributes:

- The data are grouped for incidence rates.
- The AFIP extensively studied the medical effects on these individuals and has precise inside-building locations for each. A cursory survey for Hiroshima located 771 individuals in only six buildings (Groce, 1980).

- The locations of these specific concrete buildings are well known.
- Individuals in the concrete buildings had no thermal injuries and less-severe blast injuries, even though they received high radiation doses.
- The RERF, who also studied most of these same individuals, had excellent shielding descriptions but poor dosimetry (globe technique).
- The U. S. Strategic Bombing Survey (1947a, 1947b) made extensive studies of these buildings using detailed architectural plans, many of which still exist.

This group of individuals is well documented, but the lack of accurate dosimetry because of the complicated shielding has prevented any extensive use of the data. Accurate dosimetry for several hundred individuals in a few selected buildings would yield enhanced information on the following:

- Radiation mortality in the dose ranges near and considerably below LD_{50}. Present dose–response curves for 5 to 10% mortality are very uncertain.
- Hematology (blood levels) vs. dose. This would allow better correlation with animal experiments than present data from accidents (highly nonuniform) and cancer treatment (localized, protracted irradiation, or complicated by disease).
- Radiation-injury level vs. dose. Analysis of the severity of nonlethal injury in even the crudest classifications (none, light, moderate, and severe) would enhance our ability to estimate impairment and possible medical workload in radiation disasters.

Three-dimensional combinatorial-geometry models of two or three buildings (Hiroshima buildings No. 24 and No. 26 seem appropriate) would be constructed to include all major shielding surfaces, such as exterior and interior structural walls, floors, and roofs, and the correct percentage of window and door openings. Adjoint calculations with MORSE–VCS would be performed by a procedure similar to that described for residential dwellings. Transmission factors would be calculated by folding the Monte Carlo output with the DOT FIA calculations.

Analysis of Hiroshima building No. 26 could also yield meaningful comparisons of the dose and medical histories. The USSBS report states:

> The Chugoku Electric Building is a five-story building of reinforced concrete located 2,100 ft from ground zero. There were casualties due to radiation on all floors on the side near the bomb, many others on the fifth and fourth floors, and some on the third floor. Those people on the first and second floors, away from the bomb blast and shielded by the upper floors, showed no radiation disease.

The USSBS descriptions can be supplemented with data available from the RERF.

After a building is modeled, an average building-transmission factor could be accurately calculated by sampling positions on the basis of where the people were most likely located. The several specific locations of interest would be calculated for each building but perhaps with less accuracy. Thus the final result would be the average neutron and gamma-ray transmission factors and the variations at several positions. The results of the adjoint calculations would be stored on magnetic tape so that in future studies the effects of other energy-angle incident fluences could be analyzed without repeating the building calculations.

SUMMARY

The atom bombs exploded at Hiroshima and Nagasaki produced radiation environments that were significantly different from the environment used to measure and to model transmission factors for neutrons and gamma rays for the T65D system. Preliminary estimates show that the gamma-ray transmission factors currently used in the T65D should be reduced on the average by factors of 1.6 to 2.0.

A calculational procedure for reevaluating transmission factors for survivors in residential areas at Hiroshima and Nagasaki is currently being validated by comparison with the BREN experiments. This procedure, in which adjoint Monte Carlo computations are used, can be applied to Japanese residential building clusters. A sufficient number of transmission-factor results can be generated from this procedure to enable development of new models based on available information in the RERF data base for application to revised dosimetry assignments for the survivors.

This same calculational procedure can be applied to two other important dosimetry problems: (1) the transmission factors for survivors in the Mitsubishi plants at Nagasaki and (2) the transmission factors for survivors with good medical histories in concrete buildings.

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DISCUSSION

Auxier: Dr. Woolson, in all the years I've been associated with this, you're the first individual I've ever seen who has accurately and correctly summarized the exact approach used by the group in developing the shielding factors. You have followed in great detail the logic of Ritchie and Hurst (1959) and all the CEX reports (see, for example, Cheka et al., 1965) through 1965. The only disturbing thing is that you are, today, at the same stage the experimental program was in the period 1957 to 1960. You are starting out on a beautiful calculational approach that we hope will lead to precisely the results we want; however, at the end, the verification of your model will be based on the BREN data, and the same logic we used in breaking out the various parts of the BREN data will be used to test the model again. The reason for questioning the results relates to the uniqueness of the two weapons, which you cannot model and test; thus we could be arguing 20 years from now, with the next generation of computer people, whether or not you did a good job in verifying that spectrum. The primary strength you have is new computer capability, but the weakness is that, if you have to compare that system against experimental data which you are questioning in the first place, then you won't be able to resolve the problem clearly, in my opinion.

Woolson: I am not questioning the experimental data. What I'm questioning is the application of that experimental data to the situations at Hiroshima and Nagasaki. We have a good verification of our calculational procedures if we get good comparisons of our calculations for the BREN neutron and gamma-ray environments with the experiments. The fact that there were fewer neutrons at Hiroshima and Nagasaki does not necessarily negate the accuracy of a calculational procedure validated by comparisons in which that neutron component is larger. If we can calculate individual neutron and gamma-ray components, then we can certainly scale them for the situation at Hiroshima and Nagasaki.

Auxier: I agree with that, and I follow your logic. But there are aspects that you can't check, because the soft spectrum has a bigger impact than the ratio. You can change the ratio easily in a computer. It's the spectral dependence that you can't mock up.

Woolson: There will always be some things we cannot precisely verify—we have to do the best we can.

Rossi: Your discussion of building-shielding factors has a disturbing aspect. The physical information generally available for epidemiological analysis provides only one dose-related datum, i.e., the total tissue kerma at the location of each individual in a cohort. Because neutrons were more effectively attenuated by buildings and also produced secondary gamma radiations in the walls, the fraction of the total kerma that was due to neutrons was considerably less inside buildings than in the open. Therefore a given total kerma was biologically less effective in the buildings, and a study of cancer incidence vs. kerma at Hiroshima loses meaning if neutrons were of any importance.

Woolson: That's right. You must consider carefully how the components of the original free-in-air environment actually produce dose in the body. In particular, to determine RBE (relative biological effectiveness), you need to know the ratio of neutron dose to total gamma-ray dose at the organ, which may be substantially different from the free-in-air kerma ratio.

Song: I have two concerns related to your calculation of radiation fields inside Japanese buildings. My first concern is the source term. In the early 1960's some experiments were conducted at the Nevada Test Site to determine the effects of ground roughness on reflected radiation fields. I recall that the rough ground perturbed the reflected radiation field, causing significant reduction of intensity and softening of the spectrum compared to the radiation field over smooth ground. Therefore, if you used an unperturbed (smooth-ground) radiation field outside the building as a source term and calculated the transmission of the radiation through building structure to estimate the radiation field inside the building, your estimate would be in error. The error would arise not because of the method of calculating the transmission but because of using a wrong source term. Second, I am concerned about the modeling of the Japanese houses. My feeling is that your modeling may not accurately represent the real Japanese housing patterns. For example, it is very rare in Japan to find a single house in a larger lot, such as you may see in the United States. Most of the urban Japanese houses, of pre-World War II construction, abut each other but are segregated either by exterior walls or by walls that surround very small inner gardens of 10 to 20 ft^2. Therefore the residential area is neither a continuous, big single building nor a collection of single small buildings separated by empty spaces. These details of housing construction probably have significant effects on the interior radiation field and should be taken into account.

Woolson: The example you give refers to the effects of surface roughness on the dose from fallout. The burst heights were too high to produce fallout. However, you are rightly concerned that the assumed free-in-air environment is, in fact, perturbed by the houses and that this technique does not take that perturbation into account in the initial transport calculation of the free-air environment with the DOT code. You are also concerned that the houses in the immediate vicinity of the survivor will have a large effect which we do not address in our procedure. I did not discuss during my presentation the way we intend to perform the free-in-air calculation, which is, in fact, different from the calculations reported at this symposium by Loewe and by Pace (see papers in this volume). However, I brought along a sketch (Fig. 1) which depicts our calculational model. Our model includes, in addition to the flat ground, an average density of building material, called a building mush, to account for the perturbation of the free-in-air environment caused by the presence of buildings not in the immediate vicinity of the subject location. This calculation is then folded with the adjoint transport calculation for the building cluster as a function of range from the burst, as shown in the figure, to give the radiation transmitted to the subject location. As for your second question—as I discussed in my presentation—the effects of neighboring buildings, in addition to the building containing the subject location, are treated in the adjoint Monte Carlo calculation by modeling a cluster of several houses in a typical residential arrangement. The effects of nearby buildings are

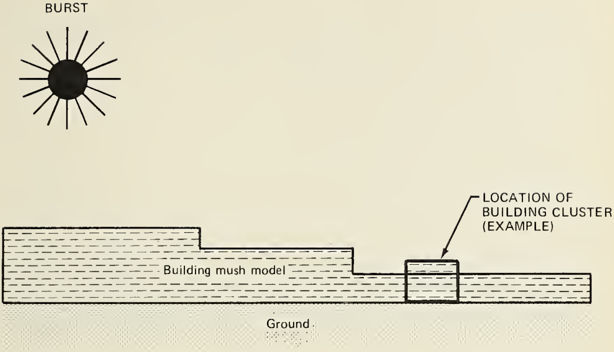

Fig. 1 Model for free-field radiation environment calculation.

more dependent on details of the house construction and layout than those of the fall-off buildings that are treated in the mush model. The full three-dimensional modeling of the cluster permits us to account for these important local perturbations in the environments. It is our belief that calculations with one or two cluster models can be generalized for most survivor locations in residential areas. Certainly, more examples can be calculated in this way than were measured during the BREN experiments.

Ellett: We hope the end point of all this will be to get a new set of tentative doses for all the survivors, and there are a great many survivors. As I understand it, for each survivor the nine T65D parameters are now on tape with identifiers for the individual. Do you think it would be possible to formulate your new results in equations similar to that nine-parameter equation so that essentially the same information could be used and we would not have to go back and look at every survivor and his location again?

Woolson: I'm sorry I failed to mention that we plan to do that. One of the constraints we are operating under is to use the data available in the data base to arrive at final transmission factor models. I think we can do it, and we will certainly try. I don't think we have any other choice.

Ellett: Dr. Auxier brought up the question of what new machines will be doing in computations 20 years from now. I really don't care. We are still working on *tentative* doses, and the actual doses survivors received won't change with time. We should quit looking for a final answer and just look for improved estimates of the dose.

Woolson: That's right. Any new system for calculating doses should be constructed in such a way that it will facilitate updates in the future as improvements are made or as new things are learned.

Bartine: The neutron dose estimate is obviously becoming lower. The neutron transmission factors originally estimated probably aren't too bad; they are probably adequate for what we are doing. We don't expect any big changes in the neutron transmission factors, do you?*

Woolson: Yes, with some reservations. Neutron transport is affected by the presence of hydrogen, and I want to investigate, in a preliminary way, the equivalency of the hydrogen in the construction material used at BREN and the expected normal hydrogen content of the walls at Hiroshima and Nagasaki. This is one possible source of lowering or raising the neutron transmission factors. Another thing is the difference in the neutronics of the house walls and the house roofs in Japan, about which I don't have any comments. Those are things that I want to look at before I say yes.

Bartine: The point was that the neutron dose was not a large part of the total dose. Overriding that is the gamma dose, primarily from secondaries. In the range where there are a large number of survivors, gamma-ray secondary production tails off sharply. The incident gammas are coming in air to ground, and you're dealing primarily with a line-of-sight type of calculation, even though some are scattered. For that condition, the ^{60}Co source measurements taken at BREN should be very indicative of the gamma transport. It is fairly well known and fairly accurate. If you can compare calculations with BREN for one energy region, you can do calculations for different energy spectra and should get good results.

Woolson: Good point. I agree.

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*Although discussed briefly in the text, neutron transmission factors were not mentioned during the oral presentation.

Dosimetry Studies in Japan

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ABSTRACT

In 1967 the National Institute of Radiological Sciences in Chiba estimated the radiation doses in air from the atomic bombing of Hiroshima and Nagasaki by using some building materials exposed to the nuclear explosions in both cities. These estimated doses were in good agreement with the doses estimated on the basis of the Ichiban project by the research group at Oak Ridge National Laboratory which were the basis for the Atomic Bomb Casualty Commission's tentative 1965 radiation dose (T65D). Recently the radiation doses in Hiroshima and Nagasaki have been reevaluated by Lawrence Livermore National Laboratory and Oak Ridge National Laboratory. In Japan a new research group was started last August, with the intention of making new estimates of doses from the atomic bombs in cooperation with U. S. research groups.

Studies on the late effects of instantaneous whole-body exposure in survivors of the atomic bombing of Hiroshima and Nagasaki require the best possible estimates of the primary gamma-ray and neutron doses received by survivors. American and Japanese scientists have made efforts to determine radiation doses from the atomic bombs (Wilson, 1956; Ritchie and Hurst, 1959; Auxier et al., 1966; Yamazaki and Sugimoto, 1953; Sugimoto, 1953; Sugimoto and Kimura, 1953; Tamaki and Hamada, 1953; Hashizume et al., 1967). In the days immediately after the nuclear explosions, Japanese teams of scientists and medical experts surveyed residual radioactivities at various sites in both cities. The survey data have given valuable information to provide a clue to the effects of atomic bombs. It was impossible, however, to estimate gamma-ray and neutron doses in free air with these survey data.

At the end of 1961, the National Institute of Radiological Sciences (NIRS) started work on a project to estimate the radiation doses in air, at the request of the Atomic Bomb Casualty Commission (ABCC). In 1960 N. Saito of the Ministry of Education suggested that the activation of ^{59}Co present as an impurity in iron could be used to determine the thermal neutron dose in Hiroshima and Nagasaki. Hashizume et al. (1967) measured the radioactivities of ^{60}Co induced in iron samples collected from the surfaces of buildings directly irradiated by the atomic bombs, but the variation in the data was so large they could not determine precise neutron doses. The variations might be due to scattering of neutrons on the surface. On the assumption that thermal neutrons were produced by the interaction of fast neutrons with concrete materials when ferroconcrete buildings were irradiated with neutrons from the atomic bombs, Hashizume et al. (1967) measured the ^{60}Co activity in iron bars imbedded in the ferroconcrete buildings to estimate neutron doses. At that time the thermoluminescence phenomenon in certain substances having ionic crystals, when exposed to ionizing radiation, was known. Ichikawa, Higashimura, and Sidei (1966) and Higashimura, Ichikawa, and Sidei (1963) made gamma-ray dose assessments from measurements of thermoluminescence yields produced in roof tiles collected within 1000 m from the hypocenter in Hiroshima and Nagasaki. Since, however, the roof tiles had been on Japanese wooden houses and all the wooden houses within 1500 m from the hypocenter were destroyed by the atomic bomb blast, the exposure factor of each roof tile was not accurately known. The thermoluminescence yields varied from sample to sample even for roof tiles collected at the same sites. Hashizume et al. (1967) also estimated gamma-ray doses from the thermoluminescence of bricks and ornamental tiles collected from existing buildings or walls. The exposure factors of bricks and ornamental tiles were known accurately. When these dose assessments were carried out, the only information on the spectra of neutrons and gamma rays from the atomic bombs was that given in S. Glasstone's book, *The Effects of Nuclear Weapons* (1962). To obtain similar spectra, Hashizume et al. (1967) used neutrons produced by bombarding a thick beryllium target with 2.5-MeV deuterons accelerated in a Van de Graaff accelerator and a gamma-ray field generated by high-energy X rays from a medical linear accelerator, a ^{137}Cs and a ^{60}Co gamma-ray source, respectively, as the neutron and the gamma-ray source for preliminary work on dose estimation.

Since the activation cross section of ^{59}Co is dominant for thermal neutrons, the distribution of thermal neutrons in a concrete block having the same elementary composition as the concrete in the buildings in Hiroshima was determined for neutrons both from the Be(d,n) reaction and from the Health Physics Research Reactor (HPRR) by using ^{59}Co needles. The distribution of thermal neutrons in the concrete block exposed to fission neutrons was calculated with two-group transport theory. As shown in

Fig. 1, the distribution of thermal neutrons had a maximum value at a depth of about 8 cm from the surface of the concrete block. On the other hand, the distribution of thermal neutrons in the concrete block exposed to slow neutrons was determined experimentally with a slow neutron source obtained by surrounding the beryllium target with paraffin blocks, using the Van de Graaff accelerator. The thermal-neutron distribution was again calculated by transport theory. These experiments showed that thermal-neutron fluence at a depth of 8 cm in the concrete was reduced to one-third of the thermal-neutron fluence at the surface. These results led Hashizume et al. (1967) to use iron samples imbedded at a depth of about 8 cm from the surface of ferroconcrete buildings in both cities for neutron dose estimation. For determining the contribution of incident slow neutrons to the total activity of iron samples imbedded at a depth of 8 cm, samples of iron located at the surfaces of corresponding buildings were collected.

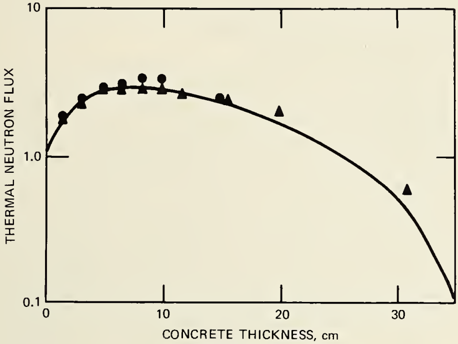


Fig. 1 Distributions of thermal neutrons in concrete irradiated with fast neutrons from the Health Physics Research Reactor (HPRR) and with Be(d,n) reaction neutrons. ▲, Be(d,n). E_d = 2.5 MeV. ●, HPRR.

Iron bars, bricks, and ornamental tiles were collected from the concrete and the walls of existing buildings, which satisfied the following conditions:

1. The walls of the building had been exposed directly to radiation from the atomic bombs without the interference of any large object to scatter the radiation.
2. The samples were located at least 1 m above ground level or on the rooftop.
3. Concrete buildings had a wall thickness greater than 25 cm.

The radioactivities of ^{60}Co in iron samples were measured with a coincidence-type beta-ray scintillation spectrometer after chemical separation and purification. Thermoluminescence was measured with a self-made reader because a commercial apparatus was not available at that time. For the thermoluminescence of bricks and ornamental tiles, the linearity between thermoluminescence yield and gamma-ray dose, dose-rate dependency, thermoluminescence fading effects, and sensitivity to neutrons were determined in a preliminary study.

We are sure that the measurements of ^{60}Co activity and thermoluminescence are correct. For dose estimations, however, these measured values should be converted into absorbed doses in units of rads. Hashizume et al. (1967), using the iron samples irradiated in the concrete block with a known neutron dose from the HPRR at Oak Ridge National Laboratory, determined conversion factors experimentally to convert the specific activity of ^{60}Co into absorbed dose. The resultant neutron doses were in good agreement with the ORNL data, as shown in Fig. 2(a). For gamma rays the factors for conversion from thermoluminescence to absorbed dose were determined with a photon source spectrally equivalent to the atomic bombs; this bomb radiation was simulated by a mixture of 6-MV X rays from a medical linear accelerator and gamma rays from both ^{60}Co and ^{137}Cs. The gamma-ray doses estimated by Hashizume et al. (1967) were also in good agreement with the ORNL data [Fig. 2(b)].

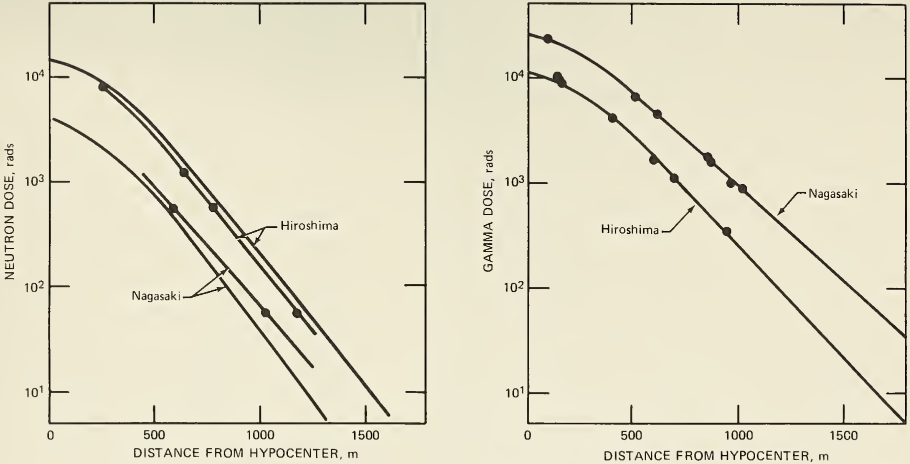
If the radiation spectra used for dose estimation by Hashizume et al. (1967) are not correct, the estimated doses should be reevaluated on the basis of precise spectra. In Japan the dose estimates for survivors in Hiroshima and Nagasaki are very important for two reasons: (1) for purely scientific purposes the relationship between radiation dose and effects needs to be known and (2) the dose received is the basis for the socioeconomic aid and medical care provided to the survivors. After the workshop on atomic bomb dosimetry held at Minneapolis, we established a Japanese project team for evaluating the radiation doses from the atomic bombs in both cities:

Chairman

Tadashi Hashizume	The University of Azabu

Members

Shojiro Fujita	Radiation Effects Research Foundation
Yoshio Okamoto	Radiation Effects Research Foundation
Hiroaki Yamada	Radiation Effects Research Foundation
Yoshikazu Kumamoto	National Institute of Radiological Sciences
Takashi Maruyama	National Institute of Radiological Sciences
Masaharu Hoshi	The University of Hiroshima
Shunzo Okajima	The University of Nagasaki



(a) (b)

Fig. 2 Air dose due to (a) neutrons and (b) gamma radiation in Hiroshima and Nagasaki as a function of horizontal distance from ground zero. ——, T65D. •—•, from T. Hashizume et al. (1967).

In August 1981 Dr. Loewe visited Japan and lectured about the new dose estimates at Lawrence Livermore National Laboratory; so the members of the project team have learned about his new dose calculation. We also obtain information about the present status of new dose evaluations in the United States from scientific journals. At the end of August, the project team had its first meeting and we discussed what should be done and what can be done to reevaluate the radiation doses in Hiroshima and Nagasaki. For our reevaluation we need the precise spectra of radiations from the atomic bombs in Hiroshima and Nagasaki which the authorities concerned consider to be the most accurate.

Shunzo Okajima, a member of the project team, is carrying out neutron-dose estimation by measuring the radioactivity of ^{152}Eu induced in stone from walls by the neutron capture reaction. We expect his work to provide satisfactory results although it may be difficult to collect samples because most of these stones are being used in protective barriers beside creeks or in house foundations. At present the project team is collecting iron samples and bricks and ornamental tiles from the remaining buildings exposed to atomic bombs and is trying to determine the chemical compositions of concrete materials. We will determine the conversion factor by using radiation sources spectrally simulating the atomic bomb radiations on the basis of precise spectra. After this we can make new dose estimates for the survivors and will calculate the organ or tissue doses to determine the dose–effect relationship. For this work, we would like a Joint Commission on Dose Evaluation of the United States and Japan to be established as soon as possible.

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DISCUSSION

Jablon: Dr. Maruyama has asked me to say something about the view of the Government of Japan with respect to the dosimetry problem. The Japanese, of course, have the same interest that we have in the problem from the scientific point of view, but they have an additional problem. The tens of thousands of survivors of the bombing who live in Japan pose an important social problem for the government. Japan has an Atomic Bomb Survivors Medical Treatment Law (in translation), under the terms of which survivors who meet certain exposure criteria receive medical treatment. The possibility that all the dosimetry on which these entitlements were based was incorrect naturally creates quite a sensation. Dr. Maruyama pointed out that the circumstances require the very closest coordination between the work being done in the United States and that being done in Japan, and it is essential for the government and people concerned in Japan to feel that they are being fully informed and that they can participate in the reevaluation. Our intention at the National Academy of Sciences, which represents a direct link to the Radiation Effects Research Foundation (RERF) for the United States, is to set up a formal liaison procedure between the American and the Japanese efforts. I don't know exactly how, but we are going to do it in a way that succeeds.

Levin: Recently we have reanalyzed some of the data on early effects—that is, within 60 days of the bombings—from Hiroshima and Nagasaki survivors. We have had access only to the data gathered by the American investigators under Ashley Oughterson (Oughterson and Warren, 1956). I wonder if there has been any attempt at evaluating the early effects using the data base expanded by the Atomic Bomb Casualty Commission (ABCC). I understand that additional cases were gathered for 5 or 6 more years. I don't know if any of the people at this meeting were in Japan in those years, but I wonder if you or others know whether any attempt has been made to analyze the very early effects. If not, could we have some cooperative effort—could you share the information that you have with us?

Maruyama: I am interested in only the stochastic effects such as leukemogenesis and carcinogenesis as a result of the atomic bomb radiations in Hiroshima and Nagasaki. Thus I can't answer your question. I believe that the RERF does have data on the early effects.

Jablon: One of the questions of immediate concern was the early effects of radiation on survivors. The best information on early effects was the material gathered by the Joint Commission for the Investigation of the Effects of the Atomic Bomb in Japan (see Oughterson and Warren, 1956), and these individual survey forms and tissue specimens were taken back to the United States where they were kept in the Armed Forces Institute of Pathology (AFIP). Later the people of Japan began to make known their resentment of the fact that this information, which was important to them, was back here in Washington; so we arranged to microfilm the Joint Commission records, and these copies are now in Japan—in Hiroshima and Nagasaki—in the medical records of the survivors to whom they pertain. The original records are still at the AFIP.

Levin: Let me clarify my question. We do have copies of the AFIP data, but later, when the shielding study was done, the ABCC obtained much more detailed data and many more cases, including location and shielding, than the original AFIP set. The ABCC and its successors, to my knowledge, have studied only the late medical effects such as leukemia and cancer. We are also interested in the early medical effects such as vomiting, hair loss, and diarrhea, and we believe that the data gathered later would allow us to estimate doses associated with those effects more accurately. Would it be possible for the medical community to make some cooperative effort—or has this analysis been done already?

Radford: We have heard a series of papers in which each stage in the analysis of the dosimetry has been discussed. George Kerr and Bill Loewe gave the impression that regarding the free-in-air doses there is now general agreement—certainly for neutrons and possibly also for gamma rays in the two cities. Obviously there is somewhat less general agreement, and work is still progressing, with regard to the transmission factors both in the housing and in the individuals. The general questions remaining are as follows: Can those of us who are interested in the biomedical aspects carry away from this meeting any feel for the extent to which the new evidence now is agreed upon by the physicists? Are we talking about perhaps a very small uncertainty in the neutron doses, a somewhat larger uncertainty in the gamma doses, and some uncertainty in the transmission factors? What range of reliability can now be attached to the new dosimetry?

Maruyama: I can't answer Dr. Radford's question, because I don't have enough basic information to determine whether the new dose estimates are correct or not. I think the T65D should be reevaluated on the basis of data that most scientists support. Agreement on the dose is needed to analyze consistently the radiobiological data.

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Self-Shielding Factors

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ABSTRACT

Historically, radiation exposure intensity has been convenient to report in terms of kerma-weighted fluence. However, use of these values, such as air dose and kerma free in air, as numbers of merit in general correlative studies with radiation-induced health effects is often inappropriate and may be misleading. This is particularly true for incident-neutron radiation, in which case neither the quantity nor the quality of radiation at sensitive sites within the body is likely to resemble that of the incident fluence.

Throughout the last two decades many efforts have been made to estimate the effect of body self-shielding on organ doses from externally incident neutrons and gamma rays. These began with the use of simple geometry phantoms and have culminated in the use of detailed anthropomorphic phantoms. In a recent effort, adjoint Monte Carlo analysis techniques have been used to determine dose and dose equivalent to the active marrow as a function of energy and angle of neutron fluence externally incident on an anthropomorphic phantom. When combined with fluences from actual nuclear devices, these dose-to-fluence factors result in marrow dose values that demonstrate great sensitivity to variations in device type, range, and body orientation.

Under a state-of-the-art radiation transport analysis demonstration program for the Japanese cities, sponsored by the Defense Nuclear Agency at the request of the National Council on Radiation Protection and Measurements, the marrow dose study referred to above is being repeated to obtain spectral distributions within the marrow for externally incident neutrons and gamma rays of arbitrary energy and angle. This is intended to allow radiobiologists and epidemiologists to select and to modify numbers of merit for correlation with health effects and to permit a greater understanding of the relationship between human and laboratory subject dosimetry.

Historically, radiation exposure intensity has been convenient to report in terms of kerma-weighted fluence, integrated over energy and angle. These integral values have been referred to variously as "air dose" and "tissue kerma free in air" and have been reported in units of rads. Although such values have been adopted by epidemiologists from time to time as numbers

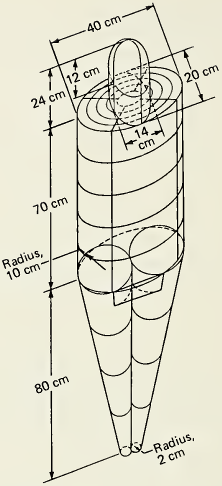
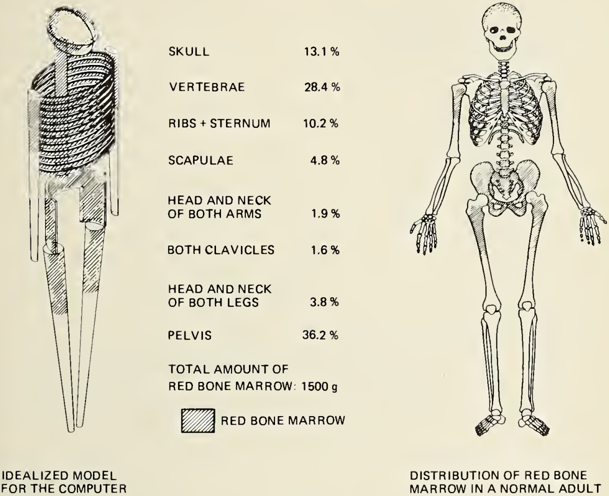


Fig. 1 Adult human phantom.

of merit for use in correlative studies, they represent an incomplete and often inappropriate basis for general correlative purposes.

A more appropriate number of merit can be obtained by determining the intensity of the radiation field at a site within the body, the sensitivity of which has previously been associated with an effect of interest. A classic example of an effort to obtain values for radiation intensity at various depths in tissue is that described by Auxier, Snyder, and Jones (1968). In that work neutron and gamma-ray fluence distributions were determined by Monte Carlo radiation transport analysis for monoenergetic, monodirectional neutrons incident on a cylindrical phantom. This work became part of the basis for NCRP neutron radiation protection standards (National Committee on Radiation Protection and Measurements, 1971).

The advent of a standard anthropomorphic phantom (Snyder et al., 1974; International Commission on Radiological Protection, 1975), shown in Fig. 1 with skeletal detail in Fig. 2, enabled the calculation of standard organ doses from various types of externally incident radiation. Such calculations were made for incident gamma rays by Jones et al. (1973) and by O'Brien and Sanna (1976). Calculations were made for incident neu-



SKULL	13.1 %
VERTEBRAE	28.4 %
RIBS + STERNUM	10.2 %
SCAPULAE	4.8 %
HEAD AND NECK OF BOTH ARMS	1.9 %
BOTH CLAVICLES	1.6 %
HEAD AND NECK OF BOTH LEGS	3.8 %
PELVIS	36.2 %

TOTAL AMOUNT OF RED BONE MARROW: 1500 g

▨ RED BONE MARROW

Fig. 2 Idealized model of the skeleton for computer calculations (left) and a more realistic representation (right) with percentages of red bone marrow found in the shaded portions of the bones. Clavicles and scapulae are not shown in phantom.

trons and gamma rays by Jones (1976) and by Kaul and Jarka (1977) with some application to Japanese city dosimetry described by Jones et al. (1975). Results of these calculations differed on an absolute basis because of variations in computation methods, cross sections, and kerma values. However, all results showed similar trends for variations in energy and angle of incidence. The most detailed of these calculations are those by Kaul and Jarka, which form the basis for the remainder of this paper.

Calculations were done by using the MORSE Monte Carlo code with combinatorial geometry (Straker, Scott, and Byrn, 1972). Cross sections having 37 neutron–21 gamma-ray energy group detail and P_3 Legendre expansion for angular definition were used (Bartine et al., 1977). The phantom used was that referenced previously by Snyder et al. (1974). These calculations were made in the adjoint mode, in which radiation is followed backward from the dosimeter until it leaks from a coupling surface. In this analytical process, scattered radiation gains energy, and

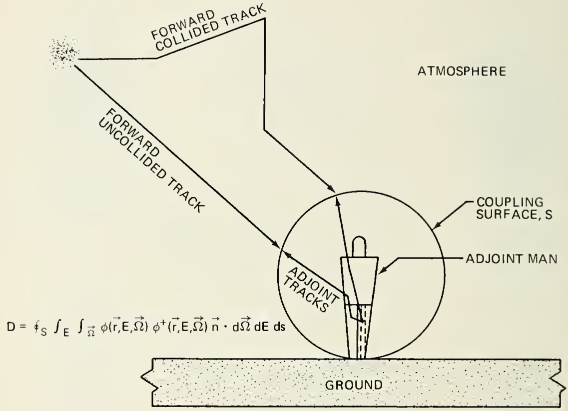


Fig. 3 Illustration of forward-adjoint coupling.

gamma rays may become neutrons. The leakage fluence can be regarded as the detector response weighted by transport to the coupling surface and can be coupled with any incident-radiation field defined at that surface to obtain a dosimeter reading. This process is shown in Fig. 3.

Adjoint fluence values were obtained for the eight marrow regions shown in Fig. 2 and for reference man according to the marrow distribution shown in that figure. Data were in 37 neutron and 21 gamma-ray energy groups and 12 equal solid-angle bins, as shown in Fig. 4. Angle-integrated values for reference man are shown in Figs. 5 to 7 for dose from incident gamma rays, ion-deposited dose from incident neutrons, and photon plus total deposited dose from incident neutrons, respectively. Also shown are tissue kerma values that would be used to obtain free-in-air dose values from the incident-radiation fluence. The marrow response for incident photons (Fig. 5) is seen to parallel the tissue kerma values over the entire Compton range ($E_\gamma > 100$ keV) with a representative marrow-dose-to-kerma ratio of 0.72, which diverges only in the photoelectric region because of increased self-shielding by the body for its marrow. For dose deposited by ions from neutron reactions (Fig. 6), the marrow response is seen to diverge from the tissue kerma values with decreasing neutron kinetic energy. However, neutron thermalization with attendant capture in nitrogen (producing a 626-keV proton) results in a lower bound

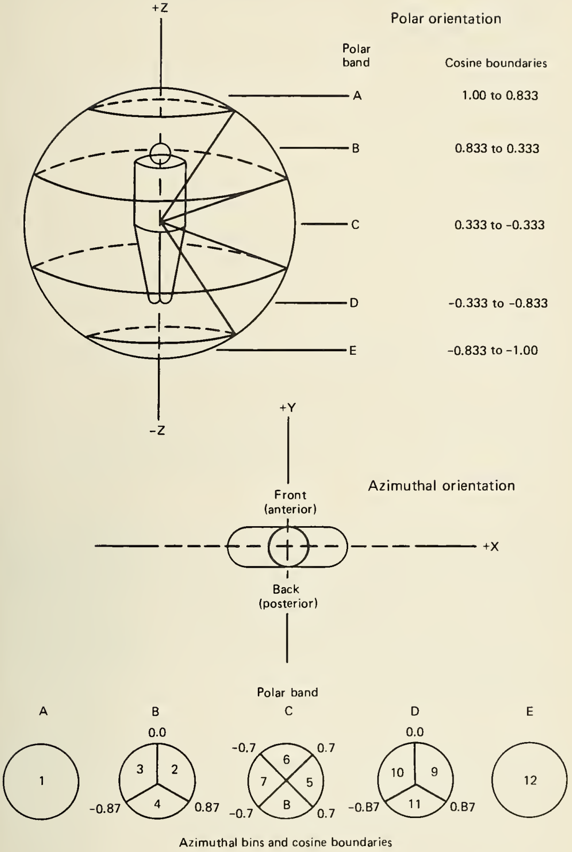


Fig. 4 **Solid-angle bin orientation for adjoint fluence exit (1.0472 steradians per bin).**

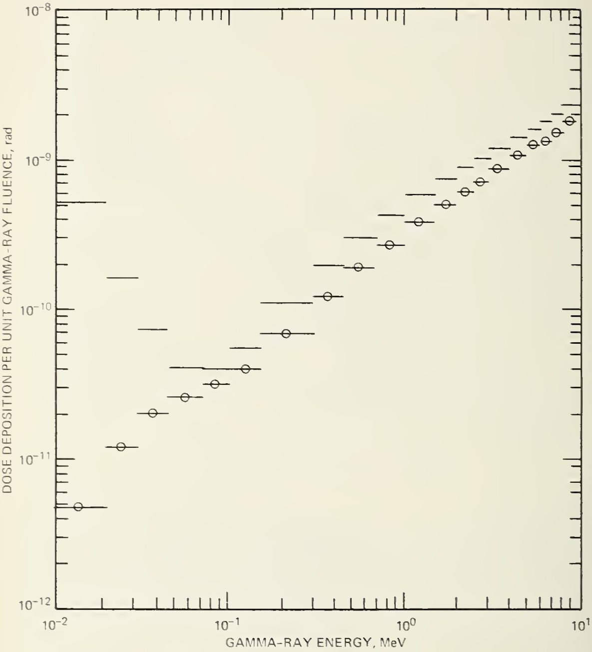


Fig. 5 Dose deposition per unit gamma-ray fluence. —, rad (tissue) free in air. ⊖, rad (red marrow) in situ.

on the marrow response. This bound exceeds the kerma value by an order of magnitude at low energies and begins to affect the neutron response at approximately 100-keV incident-neutron energy. A neutron-induced photon dose provides an even higher lower limit on marrow response from incident neutrons (Fig. 7), a full two orders of magnitude above the tissue kerma minimum.

Marrow responses described previously have been used to obtain marrow doses for several incident-neutron spectra. These include spectra for three ground ranges at Hiroshima and Nagasaki (Pace, 1981), with the very hard Bare Reactor Experiment, Nevada (BREN) source spectrum

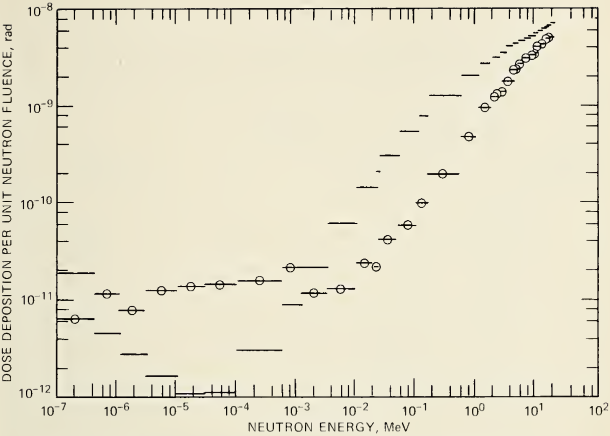


Fig. 6 Dose deposition per unit neutron fluence. ——, rad (tissue) free in air. ⊖, rad (red marrow), ion component, in situ.

(Kazi et al., 1978) and the very soft pressurized-water-reactor (PWR) in-containment fluence (Sanna et al., 1980) provided for comparison. Marrow dose values from isotropically incident neutrons having these spectral characteristics are shown as ratios to tissue dose free in air in Table 1. Dose transmission from energetic ions (D_n) at Nagasaki exceeds that at Hiroshima because of spectral differences. Spectral hardening causes such transmission to increase with range at both cities. The BREN and PWR values for D_n are the same even though these spectra are very different from each other. The harder spectrum for Nagasaki deposits less neutron-induced gamma-ray dose ($D_{n-\gamma}$) in the marrow than does that for Hiroshima. Both cities exhibit a decrease in this component as the spectra harden with increasing range. The hard BREN spectrum produces very little gamma-ray dose per unit of neutron dose free in air, whereas the very soft PWR spectrum produces a very large gamma component.

Marrow dose equivalent was also calculated for the ion portion of the dose from incident neutrons (DE_n) and for the total dose (DE_T). Although these results show some effect of spectral hardening, they are quite consistent for all the spectra except that from the PWR, as are the quality factors associated with ion dose component ($Q_n = DE_n/D_n$). On the

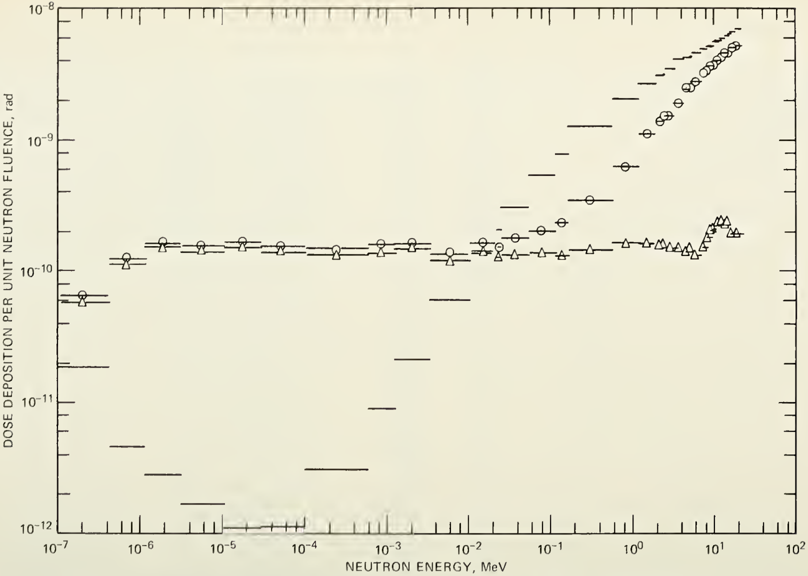


Fig. 7 Dose deposition per unit neutron fluence. ——, rad (tissue) free in air. △, rad (red marrow), n–γ component, in situ. ⊖, rad (red marrow), total, in situ.

TABLE 1

Marrow Dose and Dose Equivalent to Tissue Dose Free-In-Air (FIA) Ratios for Isotropically Incident Neutrons

	Marrow dose			Marrow dose (equiv.)			
	Tissue dose FIA			Tissue dose FIA			
Radiation field	D_n*	$D_{n-\gamma}$*	D_T*	DE_n*	DE_T*	Q_n*	Q_{eff}*
Hiroshima							
1000 m HR†	0.269	0.337	0.606	3.02	3.36	11.2	5.54
1500 m HR†	0.295	0.251	0.546	3.20	3.45	10.8	6.32
2000 m HR†	0.318	0.206	0.524	3.34	3.55	10.5	6.77
Nagasaki							
1000 m HR†	0.306	0.204	0.510	3.27	3.47	10.7	6.81
1500 m HR†	0.326	0.188	0.514	3.39	3.58	10.4	6.96
2000 m HR†	0.340	0.167	0.507	3.48	3.64	10.2	7.19
BREN source spectrum	0.333	0.066	0.399	3.50	3.57	10.5	8.94
PWR in-containment fluence	0.332	1.99	2.32	3.37	5.36	10.1	2.31

*D_n, dose transmission from energetic ions; $D_{n-\gamma}$, neutron-induced gamma-ray dose; D_T, total dose from neutrons; DE_n, dose from incident neutrons; DE_T, total dose equivalent from incident neutrons; Q_n, quality of neutrons; Q_{eff}, effective quality factor.

†Horizontal range (HR) from ground zero.

other hand, the effective quality factor ($Q_{eff} = DE_T/D_T$) is very sensitive to neutron spectrum hardness.

Table 2 shows the variation of the average marrow dose caused by nonisotropic exposure typical of neutron and secondary gamma-ray fluence at an 1166-m slant range from a boosted fission device at a 600-m burst height. These variations have the effect of dose enhancement for standing man and additional shielding for reclining man in some orientations.

Because marrow is not uniformly distributed, variations in the angular fluence can result in increases in dose for some portions of the marrow and decreases in dose for other portions. This effect is demonstrated in Table 3 for two organs and three orientations relative to the same radiation field used for the Table 2 data. These values show that for individual organs substantial dose variations are possible owing to nonisotropic fluences.

The data shown in this paper indicate that variations in energy spectra and angular distributions of incident radiation can have a substantial effect on dose to individual marrow regions as a result of body self-shielding. That dose to other organs may be similarly affected is implied. Because of

TABLE 2

Ratios of Marrow Dose from Angle-Differential Fluence to Marrow Dose from Isotropic Fluence

	Orientation to ground zero						
				Reclining man			
	Standing man			Face up		Face down	
	Facing toward	Side-on	Facing away	Head toward	Head away	Head toward	Head away
Neutron dose							
Ion*	1.0	1.0	1.2	0.9	0.8	1.1	1.0
n–γ†	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Gamma-ray dose	1.0	1.0	1.1	0.9	0.8	1.0	0.9

*Dose deposited by energetic ions.

†Dose deposited by neutron-induced gamma radiation.

TABLE 3

Ratios of Regional Marrow Dose from Angle-Differential Fluence to Average Marrow Dose from Isotropic Fluence (Standing Man)

	Orientation to ground zero		
	Facing toward	Side-on	Facing away
	Spine		
Neutron dose			
Ion*	0.6	0.7	1.0
n–γ†	1.1	1.1	1.2
Gamma-ray dose	0.9	1.0	1.1
	Clavicles		
Neutron dose			
Ion*	2.0	1.8	1.4
n–γ†	1.0	1.0	1.0
Gamma-ray dose	1.2	1.2	1.0

*Dose deposited by energetic ions.

†Dose deposited by neutron-induced gamma radiation.

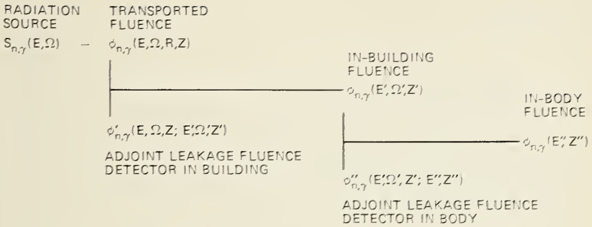


Fig. 8 State-of-the-art technical approach schematic for Japanese atomic bomb survivor exposure analysis. (Values with parentheses denote functional dependence of the forward and adjoint fluence on energy, angle, and location within the frame of reference for each calculation.)

the potential importance of such effects to epidemiological studies of latent health problems in Japanese atomic bomb survivors, a limited-scope demonstration calculation of survivor organ exposure is now under way. This program has been sponsored by the Defense Nuclear Agency at the request of NCRP to demonstrate the use of state-of-the-art calculation techniques on the problem at hand. Anisotropic source characteristics, atmospheric transport, house shielding, and body self-shielding, all on a limited basis, will be considered. This program is just beginning. It is, however, possible to describe the limits of detail that may be obtained with state-of-the-art analysis techniques (see Fig. 8). The potential end product of such analysis is shown to be the energy-dependent fluence for each radiation component in each organ of each survivor for each range and shielding configuration. Such analysis is possible as a result of new developments in consistent multisized phantoms (Cristy, 1980, 1981) and improved multicalculation coupling techniques (Rhoades, 1974). Although this places a burden of additional data on the radiobiologist or epidemiologist who wishes to use these values, it also offers the opportunity for greater flexibility in the choice of numbers of merit for use in his studies. It also provides the potential for better cross correlation with therapeutic and accidental exposure studies as well as with those using animal subjects.

ACKNOWLEDGMENT

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DISCUSSION

Land: Would it be better to calculate organ-specific doses directly from the nine-parameter input rather than, as has been done previously, to characterize the individual by a single kerma value (an index of exposure at a point in space) and then to translate that into tissue doses for various organs? For breast tissue dose, in particular, orientation might make a difference.

Kaul: I recommend that the data base give organ doses and not free-in-air doses because from our calculations it seems clear that the organ doses vary from the averages in terms of both the quality and the quantity of the radiation. One of the problems with the dosimetry as it stands now is that integral information is coupled at too many points in the analysis. It is coupled outside the building and again at the man, and there is no transmission of differential information across those boundaries. When the boundary is crossed, an assumption is made. The usual assumption has been that the spectrum is similar to that from the BREN reactor; and it had to be made because that is where all the information came from—what else could one assume? The radiobiologist and the epidemiologist need differential organ fluence information, not just dose information, because the neutrons are such a minor component relative to the gamma rays. If the uncertainties in the gamma dose can be made low enough to allow the difference between the doses in the two cities to be attributed to the neutrons, it is likely that the effects so identified will be exceedingly subtle and will be related to the regional dose-equivalent differences for the neutrons. No good information will come out of whole-body averages.

Kerr: I was disappointed that you concentrated on neutrons because the largest discrepancies in our original calculations were in the bone-marrow dose from gamma rays. We have spent a lot of time and effort in the last couple of years in trying to resolve the discrepancies and to come up with the appropriate response function for the dose to active marrow in trabecular bone cavities, and I know you too have worked on getting a better response function. What really is important now, especially at the larger ground distances, is the dose to active bone marrow from gamma rays.

Kaul: George Kerr and I have gone around on this a few times, and I'm sorry to say that my last analysis showed that he was right and I was wrong—that is probably why I did not talk about it. That is the very reason I prefer the information to be transmitted to the radiobiologist as fluence and not as dose. Ten radiobiologists given a fluence will come up with ten different doses because they each interpret the marrow slightly differently. They may use somewhat different cavity sizes, or one may include the effect of the nearby trabecular bone because he is interested in the marrow–trabecular interface, and another one may not care about that interface but will want to know the average. There is no way that a physicist calculating this can satisfy all those different requirements with anything but fluence information. If I quote a dose in rads to the marrow, the physician will ask "Where? What? When? How? Why?" I would prefer, therefore, to participate in a discussion as to what factors to use, what charged-particle equilibrium assumptions to use, and so forth, but the basic information transmitted should be fluence information. In the particular case of the average marrow kerma, we did calculate it, and our result is in substantial agreement with the kerma you quoted recently in *Health Physics* (Kerr, 1980).

Wyckoff: First, I don't think that we are dealing here with a routine health physics situation in which the absorbed doses are low, so that we may use dose equivalent and Q's (i.e., quality factors). Second, when you take averages of absorbed dose from a given type and energy of radiation over a given organ of an individual and attempt to relate the average to an effect, you must be assuming implicitly that there is proportionality between absorbed dose and effect—at least for the range of absorbed dose involved in such an average.

Kaul: I used the Q value only to point up that, although ten times as much energy is deposited from the gamma rays as from the lower energy neutrons in terms of dose within the body, at least by one measure—that is, the Q value—the neutrons, i.e., the ions they produce, are more effective biologically per unit of energy deposition. I used the Q value because I thought that would be less controversial than applying some arbitrary RBE which I could not defend. I'll let NCRP defend its Q values. The issue of average vs. individual organ doses is that under certain circumstances an average organ dose may be useful for stipulating a risk, but for analyzing an effect you want as much information as you can get, especially when that effect may have a nonlinear component (e.g., a factor of 2 difference in peak-to-average marrow dose may translate into something considerably larger in terms of the effect being studied.) A good example of the use of other than a straight average organ dose is our marrow dose evaluation, which is done separately for eight marrow regions. For specific incident energy and angle, radiation deposition in the regions can vary over a range of a factor of 2 or more.

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Biological Indicators of Radiation Quality

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ABSTRACT

The induction of many biological effects (e.g., cancers, mutations, and chromosomal aberrations) by high linear energy transfer (LET) radiation is strikingly different in one or two respects from the induction by acute low-LET radiation. If the acute low-LET dose–effect curve is of the usual quadratic form, it becomes linear as LET increases.

In any case the linear slope increases as LET increases; that is, the relative biological effectiveness (RBE) increases. Both changes might be exploited as biological indicators of whether or not the recent recalculations of dose and of neutron contribution to dose at Hiroshima and Nagasaki seem consistent with the epidemiological observations.

The biological end points that have been extensively studied in survivors include acute effects, growth and development after in utero or childhood exposure, genetic and cytogenetic effects in offspring, somatic chromosomal aberrations in survivors, and, of course, cancers, including leukemia. No significant indication among offspring of genetic or cytogenetic effects attributable to parental exposure has been found. Among the remaining end points, only the data on somatic chromosomal aberrations and on cancers appear robust enough to allow one to draw definite inferences by comparing experiences at the two cities. Even for these data the sparsity of the Nagasaki data constitutes a problem, precluding meaningful dose–effect curve analysis. Nevertheless, although the substantial differences in yields of solid cancers and of chromosomal aberrations observed for the T65D for the two cities still persist when the recent Lawrence Livermore National Laboratory dose estimates are used instead, the later dose estimates appear somewhat more biologically reasonable, at least with regard to the aberration data.

A basic reason for the importance of the questions regarding the physical dose estimates for the atom bomb survivors at Hiroshima and Nagasaki is that the epidemiological data—collected first by the Atomic Bomb Casualty Commission (ABCC) and more recently by the Radiation Effects

Research Foundation (RERF)—are only as good for quantitative hazard estimation as are the dose estimates. Obviously, if the dose estimates change, then our radiation hazard estimate will also, although perhaps not so significantly as has been suggested by recent press coverage. The most striking difference between the T65D estimates used until recently and the Lawrence Livermore National Laboratory (LLNL) estimates described by Loewe and Mendelsohn (1981) lies in the much lower estimates of the relative magnitude of the neutron component of dose at Hiroshima. This is important because it affects not only the health effects estimates for the gamma-ray component of dose at Hiroshima but also our estimates of the hazards associated with human neutron exposures (Rossi and Mays, 1978).

Many of the questions regarding the doses received by the survivors, especially at Hiroshima, have not yet been resolved. Not only are there questions with respect to weapon yield, neutron leakage, and transport effects, but there are also uncertainties with respect to shielding factors. Ultimately, only after new tissue dose estimates have been calculated for the large groups of survivors involved in the ABCC–RERF epidemiological studies will it be possible to refine our health hazards estimates appreciably.

The epidemiological data are not, however, utterly dependent on the physical dosimetry. We have enough basic radiobiological knowledge to make some judgments about dose. In fact, although it may seem somewhat presumptuous, some biologists (including ourselves) feel certain enough about some aspects of the radiobiology involved to question whether physical dose estimates make sense in light of the epidemiological data available and even occasionally to use "biological dosimetry" and make dose estimates on the basis of biological observations. The extensiveness of the data available from the epidemiological studies by ABCC–RERF prompts us to examine the extent to which these data might provide some clarification, particularly regarding the relative neutron contribution to dose at Hiroshima.

DOSE–EFFECT CURVES

Much is known regarding the shapes of radiobiological dose–effect curves [see the BEIR III Report of the Committee on the Biological Effects on Populations of Exposure to Low Levels of Ionizing Radiation (BEIR) (1980) for a somewhat more detailed discussion]. What is generally observed for acute doses of radiation of low linear energy transfer (LET) is a quadratic relationship, with saturation evident at the higher doses, of the form

$$F(D) = (\alpha_0 + \alpha_1 D + \alpha_2 D^2) \exp(-\beta_1 D - \beta_2 D^2)$$

The first portion of the expression simply means that the effects can arise spontaneously in the absence of any added radiation and that independent ionizing events can interact to produce effects, although one ionizing event can also be sufficient. The saturation represented by the exponential term is often ascribed to cell killing but can sometimes be shown to result from site limitations, as, for example, in the induction of chromosome exchange aberrations, which requires that two different chromosomes be broken and interact. In any case, over the lower portion of the curve the saturation effect is negligible, and

$$F(D) = \alpha_0 + \alpha_1 D + \alpha_2 D^2$$

This is equivalent to the microdosimetric expression of Kellerer and Rossi (1972),

$$E = \kappa(\zeta D + D^2)$$

For some biological end points, the α_1 term is dominant, tending toward the linear expression

$$F(D) = \alpha_0 + \alpha_1 D$$

whereas, for others the α_2 term is dominant, tending toward

$$F(D) = \alpha_0 + \alpha_2 D^2$$

which is a pure dose-squared relationship.

The LET of the radiation involved affects the shapes of dose–effect curves. Generally, if the acute low-LET curve has an appreciable α_2 component, then increasing the LET tends to straighten the curve out. The generally accepted reason for this is that the increases in LET increase the probability that a single event will cause the effect, up to the point where the effect is certain to result in any cell that is "hit." Thus, for mixed radiation exposures, such as the mixture of neutrons and gamma rays from a nuclear weapon, the dose–effect curve will have two components, a term linear in high-LET dose and the quadratic relationship in low-LET dose,

$$F(D_\gamma, D_n) = \alpha_0 + \alpha_1 D_\gamma + \alpha_2 D_\gamma^2 + \beta D_n$$

Up to a point (with LET values of about 100 to 200 keV/μm), the efficiency per unit dose also increases with increasing LET, presumably because there is less and less wastage of energy deposition; beyond that point, which depends on target volume, the efficiency per unit dose goes down again, presumably because of "overkill."

Relative biological effectiveness (RBE) is an often used measure of the efficiency of effect production by a particular quality of radiation in relation to some reference low-LET radiation like gamma rays. Formally, it is the dose of the reference radiation required to produce a given level of effect divided by the dose of the other radiation required to produce the same level of effect. However, if the shapes of the dose–effect curves are dissimilar, e.g., the reference radiation curve has a significant α_2 component and the other radiation curve does not, then there clearly is no single value for RBE. In such cases, RBE is some function of dose, and a more useful concept is the so-called ultimate RBE, which is simply the ratio of α_1 slopes for the two radiations; this is the maximum value that conventionally determined RBE can attain (at infinitesimal levels of effect).

The slopes α_1 are of practical importance because for low-LET radiations there generally is a dose-rate effect for the production of biological effects: as dose rate is decreased, the effectiveness goes down until a point is reached below which further reductions in dose rate result in no further reduction in effect per unit dose. What actually happens is that the value of α_2 is reduced until it becomes zero; for low dose rates, the response curve therefore becomes linear with slope α_1 because the lesions resulting from subeffective events that can interact to produce effects related to the square of dose have limited lifetimes. If enough time elapses between one event and the next, the first event is no longer available, and no interaction can occur. As expected for dose–effect curves with essentially no α_2D^2 term, such as those for fission neutrons, no dose-rate effect is seen. Since in estimating human health hazards we are generally concerned with very low dose rates (or doses), it is the slope α_1 that matters. In the consideration of the effectiveness of high-LET radiations, such as the neutron components of dose at Hiroshima and Nagasaki, the ultimate RBE is the useful value. Although often pointed out, it is worth noting here again that the large values of ultimate RBE often reported (50 to 100) result not because neutrons are unexpectedly *more* efficient but rather because the low-LET radiations are so much *less* efficient at low doses or dose rates.

With these radiobiological considerations in mind, we can return to the question of whether the biological and epidemiological data can give any clues as to whether the T65D dose estimates are more biologically reasonable than those by LLNL. The principal difference between them, i.e., the relative magnitude of the neutron component of dose at Hiroshima, can be expressed in two ways, curve shape and efficiency per unit dose. Either might be seen as a difference between the results for the two cities.

END POINTS

The potentially useful end points are all included among so-called late effects. Some of the responses produced by radiation, including those appearing fairly promptly (such as nausea, diarrhea, and erythema) and others appearing later (such as ocular opacities or effects on the growth and development of children exposed in utero), are either characterized by dose–response curves of the threshold type or else simply uncharacterized. For none is there sufficient information to allow any useful inferences regarding the dosimetry question. For example, a number of groups have examined survivors for lenticular opacities over the years at both Hiroshima and Nagasaki. Jablon et al. (1971) reviewed the accumulated data and concluded that there might be a difference between the responses in the two cities and that the RBE of the neutron component of dose for Hiroshima which was based on the T65D doses might be about 1 to 2 for this end point. However, because of the subjective nature of the determination of lenticular opacities and because the studies in the two cities were done separately by different investigators, they concluded that a reliable estimate is not possible. Thus the data for this end point appear to be just as compatible with the T65D dose estimates as they are with the LLNL dose estimates: the larger effect at Hiroshima, if real, could easily be explained by a neutron RBE that, although larger than 1 to 2, would still be quite plausible.

Similarly, a fairly early positive finding at ABCC was that children exposed in utero or in infancy tended to grow less well. In particular, a significant reduction in head circumference (in extreme cases associated with mental retardation) was found among those most heavily exposed in utero. The data have been reviewed by Blot (1975). Again the effect appears to have been greater per unit T65D dose in Hiroshima than in Nagasaki, but the unknown influences of other factors on growth and development preclude any firm conclusion, and the data appear compatible with either the T65D or the LLNL doses.

Among the late effects for which we can assume nonthreshold dose responses of the general linear-quadratic form already discussed and for which a large amount of data has been collected are genetic effects, leukemia and cancer induction, and somatic chromosomal aberrations.

Genetic Effects

Extensive studies designed to detect various types of genetic effects among the children of survivors were started early in the history of ABCC, and some of them are still continuing at RERF. The results of these studies have recently been reviewed by Schull, Otake, and Neel (1981). An early study attempted to detect a shift in sex ratio, which was predicted because of hemizygosity of the X chromosome in the male. The result was ultimately negative, but more-recent information on mammalian sex chromosomes in any case makes the original prediction questionable. Four other genetic end points have been studied extensively: (1) pregnancy outcomes (stillbirths, malformations, and neonatal deaths in the first week), (2) mortality (1 week to 17 years), (3) chromosomal anomalies, and (4) mutations altering the electrophoretic mobility of a group of serum and red-cell proteins. Although very large populations have been studied, none of the four end points has demonstrated a statistically significant effect of parental radiation exposure at either city. Human mutational sensitivity simply appears to be too low to be detected.

Schull, Otake, and Neel noted, however, that there is actually a numerical excess for each end point among the children of exposed parents, and they used the excesses for the first three end points listed to calculate a mutational "doubling dose" (the electrophoretic variant data were not used, because the excess consists of only one case in the exposed group against no cases in the controls). The calculated doubling dose, which was based on a revision of the T65D dosimetry (revised for Nagasaki to reflect new estimates of the location of the hypocenter) and in which a neutron RBE of 5 was assumed, was 156 rems. In view of the low levels of effect, even if they are real, an attempt to separate the effects by city is not realistic. However, it seems clear that the use of the LLNL doses would not change the picture much, especially since the choice of a neutron RBE of 5 is arbitrary and the value could easily be higher. In passing, contrary to implications in the Schull, Otake, and Neel (1981) paper and in an accompanying editorial (Neel, 1981), it seems unlikely that the Hiroshima and Nagasaki genetic effects data will have much impact on our human genetic effects estimates; the BEIR III Genetic Effects Subcommittee, for example, gave their estimates as ranges spanning more than an order of magnitude because of the many uncertainties involved, of which doubling dose is but one.

Leukemia and Cancer Induction

The best-documented and most-extensive late health effect at Hiroshima and Nagasaki is the increased mortality from leukemia and other malignancies. Some curve-shape information is available, particularly for leukemia, for which it seems that all the induced cases have already been recorded. It was analysis of the leukemia data which led Rossi and Mays (1978) to raise the question of the acceptability of current radiation-protection standards for neutrons. The cancer mortality data, however, are not actually as robust as is sometimes suggested. On the basis of T65D dose estimates, data on leukemia mortality at Hiroshima suggest a strong linear component, but those from Nagasaki fit a predominantly dose-squared relationship. The Nagasaki relationship, however, is due largely to a dearth of cases in the dose groups below 100 rads; above 100 rads it appears linear, with a slope not unlike that for Hiroshima. Interestingly enough, when the LLNL dose estimates are used, as was done by Straume and Dobson (1981), the leukemia data from the two cities are in much closer agreement, and a single curve can be fitted. However, as noted by Straume and Dobson, a neutron RBE as high as 25 cannot be excluded. Furthermore, the data from Nagasaki are much less extensive than those from Hiroshima, and an acceptable single curve can be fitted through the data from both cities even with the T65D doses. For example, the BEIR III Biological Effects Committee (1980) fitted three models to the leukemia data based on the T65D doses: one "linear-quadratic" in gamma-ray dose and linear in neutron dose (called LQ-L), one linear in both neutron and gamma dose (L-L), and one linear in neutron dose and pure dose-squared for gamma dose (Q-L). Least-squares regressions yielded p values of 0.49, 0.49, and 0.42, for LQ-L, L-L, and Q-L, respectively (Table V-8, p. 184 in the BEIR-III report) which demonstrates this point dramatically.

The data for cancers other than leukemia are even less robust. For example, when the BEIR III Committee analyzed the solid cancer mortality data, the best fits to the LQ-L, L-L, and Q-L models yielded p values of only 0.23, 0.30, and 0.28, respectively (Table V-9, p. 186 in the BEIR report). Not only could no reasonable choice between models be made but also the fits all are appreciably worse than they were for the leukemia data. Worse, the parameter estimates are quite unstable, with errors often larger than the values of the estimates. Straume and Dobson (1981), using both the T65D and the LLNL doses, have fitted the data for total malignancies (including leukemias). In either case they report a significant difference between cities. If, as has been done previously, the difference between cities is ascribed to the neutron component of dose, then an RBE of as much as 100 is possible on the basis of the LLNL doses. However, as Straume and Dobson note, this is not necessarily very different from the result of similar calculations based on the T65D doses (i.e., the uncertainty is so large that RBE values of less than 10 or nearly 100 can be accommodated). Thus the cancer mortality data, extensive as they are and despite a clear-cut difference between cities, do not offer any real clue to whether the T65D doses are more plausible than the LLNL doses. That the LLNL doses appear to make some of the data for the two cities agree better (as with leukemia, for example) is small comfort when substantial differences in cancer mortality still remain. However, almost certainly the solid cancer mortality data are still incomplete, and they may become more robust in the future; this would possibly allow more discrimination between dose–effect models and perhaps some suggestion regarding the dosimetry.

The possible impact of the LLNL dosimetry on human radiation cancer risk estimates has attracted considerable attention recently. The BEIR III Committee presented cancer risk estimates that were based on fitting the Hiroshima and Nagasaki mortality data to derivatives of their three models. The derivatives, designated $\overline{\text{LQ-L}}$, $\overline{\text{L-L}}$, and $\overline{\text{Q-L}}$, were constrained as to ultimate RBE (values adopted were based on analysis of the leukemia data) [in the case of the $\overline{\text{LQ-L}}$ model, it was constrained also as to the ratio of gamma dose coefficients (a ratio of 0.0086 was derived from the leukemia data)] to allow stable estimates of the gamma coefficients to be obtained. The coefficients thus obtained were then applied to a U. S. life-table population to obtain risk estimates. Dr. Charles E. Land (1981) has recalculated the coefficients by using the LLNL doses. For the preferred $\overline{\text{LQ-L}}$ model (with the constraints recalculated on the basis of the LLNL doses), he found that the α_γ coefficient was changed from $(1.4 \pm 0.4) \times 10^{-6}$ to $(2.6 \pm 0.7) \times 10^{-6}$ cases person-year^{-1} rad^{-1}. For the "conservative" $\overline{\text{L-L}}$ model, the change was from $(3.5 \pm 0.9) \times 10^{-6}$ to $(5.1 \pm 1.3) \times 10^{-6}$ cases person-year^{-1} rad^{-1}. Clearly, the changes are small, and choices between them or between models are not possible on purely statistical grounds. Furthermore, even if the LLNL dosimetry is accepted, the impact on human risk estimates does not seem very significant in view of the many other uncertainties involved.

Somatic and Chromosomal Aberrations

Radiation exposure induces chromosomal aberrations that can be observed in cells when they later undergo mitotic divisions. The frequency of such aberrations in samples of lymphocytes from peripheral-blood samples drawn promptly after the exposure has long been used as a means of biological dosimetry in cases of accidental human radiation exposures (Bender, 1979; Lloyd and Purrott, 1981). These cells are in a pre-DNA-synthesis G_0 stage of the cell cycle while in the circulation and do not normally divide while in the peripheral circulation, but they can be made to divide in short-term tissue culture by stimulation with a mitogen such as phytohemagglutinin. Radiation of peripheral lymphocytes in vivo or in vitro yields chromosome aberrations, and yields and shapes of dose–effect curves have been accurately determined in a number of laboratories for various qualities of radiation. Thus aberration yields in a lymphocyte sample from an irradiated person can be compared with standard curves to determine the dose that must have been received.

The aberrations induced are of a number of types falling into two major classes: (1) single-break deletions and (2) exchanges involving interactions of two (or more) breaks. The latter can be either symmetrical (translocations and inversions) or asymmetrical (dicentrics and rings).

Aberrations tend to be lost as a function of time and cell division, at different rates for different types, so that at any mitosis, except the first following the radiation exposure, the frequencies observed will be lower than those induced by different amounts depending on the aberration type.

The techniques for determining aberration frequencies in human lymphocytes were not available when the ABCC started its investigations of radiation effects at Hiroshima and Nagasaki, but in the 1960's a cytogenetics program was initiated to measure the frequencies of aberrations still present in the lymphocytes of survivors. The data were most recently summarized by Awa et al. (1978); an impressive total of nearly 100,000 cells (i.e., more than 4.5 million chromosomes) was scored. As noted by Awa et al. and further analyzed by Otake (1979), there is a striking and statistically significant difference in the dose–effect curves for the two cities on the basis of the T65D dose estimates. As with leukemia, the Hiroshima data fitted a straight line fairly well, but the Nagasaki data showed a strong upward curvature, and the difference was attributed to the differences in neutron kermas for the two cities. As noted by Straume and Dobson (1981), the differences between the two cities do not disappear when the LLNL kerma values are used instead of the T65D kerma values.

To illustrate this point, we also analyzed the shapes of the Hiroshima and Nagasaki observed aberration curves for the T65D and the LLNL kerma estimates. We used the data on cells with exchange-type aberrations as presented by Otake (1979) in his Table 3, choosing exchanges over all aberrations because the exchanges were all almost certainly radiation induced. We chose the Otake subject groupings and average doses because Otake calculated the mean doses by arbitrarily reducing doses for individuals to 600 rems in cases where the T65D estimate was higher, a reasonable procedure since it seemed highly unlikely that anyone who received a higher dose could have survived. The models fitted were linear, i.e.,

$$Y = b + \alpha D$$

or simple linear-quadratic, i.e.,

$$Y = b + \alpha D + \beta D^2$$

These are the L and LQ models discussed earlier. We used Otake's average neutron and gamma T65D doses. Corresponding LLNL neutron and gamma tissue kerma values for the Otake subject groups were kindly provided by Dr. Charles E. Land, who calculated them from the curves given by Loewe and Mendelsohn (1981) by using a method of cubic splines to arrive at suitable average values. The dose groups and kerma values are

TABLE 1

Mean T65D Kerma Values and Mean Corresponding LLNL Kerma Values for Hiroshima and Nagasaki

Total T65D dose, rads	Mean T65D kerma,* rads		Mean LLNL kerma,† rads	
	Gamma	Neutron	Gamma	Neutron
		Hiroshima		
Control	0	0	0	0
1 to 69	23.3	5.6	47.2	0.9
70 to 139	87.7	24.9	140.2	4.6
140 to 209	135.0	38.1	203.8	7.3
210 to 299	191.9	57.4	279.9	11.9
300 to 499	291.8	94.8	411.8	22.2
500 to 600	399.2	142.9	549.2	35.3
		Nagasaki		
Control	0	0	0	0
1 to 69	32.4	0.03	22.9	0
70 to 139	106.0	0.5	73.8	0.1
140 to 209	168.2	2.2	117.0	0.6
210 to 299	247.6	3.9	176.7	1.2
300 to 499	374.7	6.4	277.4	2.0
500 to 600	531.6	12.6	396.0	4.2

*Otake (1979).

†Calculated by Land (1981) from data in Loewe and Mendelsohn (1981).

shown in Table 1. These were then converted to bone-marrow doses, as described below, for consistency with other analyses.

Least-squares regression analyses were done against total bone-marrow doses but with the constraint that none of the fitted parameters was allowed to be negative (which would, of course, constitute biological nonsense). The results are given in Table 2 and Fig. 1. Clearly, there is little choice between the two dosimetries for either city. With either one the Hiroshima data continue to fit the linear model quite well and the Nagasaki data to fit the quadratic model substantially better than the linear one. There can be no question, however, that the LLNL dosimetry does bring the aberration yields in the two cities into better agreement. By way of illustration, when we ran a least-squares regression of all the data from both cities against the quadratic model, the R^2 value for the LLNL kerma was an acceptable 0.964 but that for the T65D kerma was only 0.678.

TABLE 2

Best-Fit Coefficients (Aberrations per Cell per Gray of Calculated Bone-Marrow Dose) and R Values for the Observed Frequencies of Cells with Exchange Aberrations at Hiroshima and Nagasaki

(Based on Total T65D and Kerma Values for Linear and Quadratic Dose–Response Models)

Model	Dosimetry	Coefficient	R^2
		Hiroshima	
Linear	T65D	$b = 0.0$* $\alpha = 0.071$	0.996
	LLNL	$b = 0.0$ $\alpha = 0.058$	0.991
Quadratic	T65D	$b = 0.009$ $\alpha = 0.047$ $\beta = 0.009$	0.997
	LLNL	$b = 0.006$ $\alpha = 0.034$ $\beta = 0.009$	0.996
		Nagasaki	
Linear	T65D	$b = 0.0$ $\alpha = 0.033$	0.884
	LLNL	$b = 0.0$ $\alpha = 0.045$	0.892
Quadratic	T65D	$b = 0.004$ $\alpha = 0.0$ $\beta = 0.014$	0.960
	LLNL	$b = 0.005$ $\alpha = 0.0$ $\beta = 0.024$	0.963

*0.0 coefficient values in all cases result from the constraint that the values must be nonnegative.

Randolph and Brewen (1980) carried out another sort of analysis of the Hiroshima data of Awa et al. (1978), by using essentially the techniques applied in chromosome-aberration biological dosimetry, to ascertain how well the doses calculated from the observed aberration frequencies might agree with the T65D kerma estimates arrived at through physical dosimetry. Their analysis involved several factors. First, since the observations were made long after the bombings (23.5 years, average), they deter-

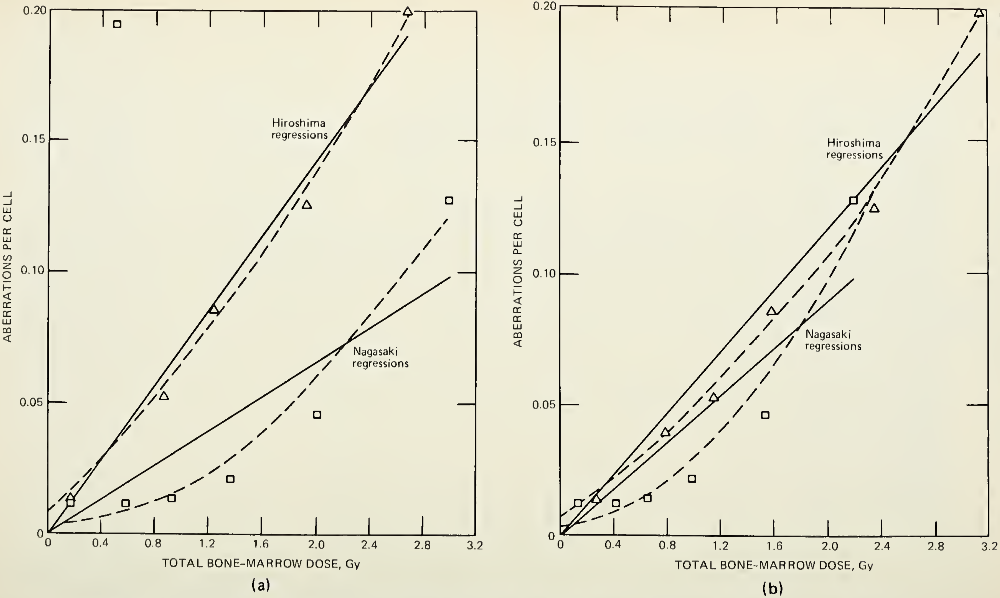

Fig. 1 Observed frequencies of cells with exchange aberrations and least-squares regressions for linear (——) and quadratic (– – –) models based on (a) the T65D and (b) the LLNL dose estimates. Δ, Hiroshima observed. □, Nagasaki observed.

mined appropriate factors from data in the literature to calculate what the frequencies of aberrations must have been immediately after the bombings. Second, appropriate coefficients of aberration production had to be selected from the literature so that the doses required to produce such frequencies could be calculated. Third, the resulting doses had to be converted into kerma values for comparison with the T65D kerma values. Kerma calculations were actually carried out for two separate aberration categories, i.e., symmetrical exchanges and asymmetrical exchanges, since the cytogenetic data were available thus broken down for Hiroshima (though not for Nagasaki) from Awa et al. (1978). In summary, the calculated kerma values generally agreed with the T65D kerma values within a factor of 2 but tended to be a bit higher than the T65D kerma values for the lower dose points and a bit lower for the higher dose points. Since no calculations were made from the Nagasaki aberration data, no comparison was possible, but the results of Randolph and Brewen do at least appear consistent with the T65D kerma values for Hiroshima.

Using the general strategy of Randolph and Brewen (1980) but in reverse, we calculated the expected aberration yields for each city for both the T65D and the LLNL kerma to see whether either set of kerma estimates produced a curve with an appreciably better fit to the cytogenetic observations. Since the Nagasaki aberration data are not broken down in more detail, we made our calculations for all exchanges rather than separately for the symmetrical and asymmetrical exchanges as did Randolph and Brewen. Also, although the Hiroshima data are presented as frequencies of aberrations per cell (which Randolph and Brewen used), the Nagasaki data appear only as frequencies of cells with aberrations, and we therefore had to use the latter to be able to compare the cities. The calculations were made as follows.

Dose

Because aberration coefficients are in terms of doses in rads, the kerma values in Table 1 had to be converted to tissue doses. Randolph and Brewen adopted conversion factors of

$$D_n = 0.26K_n$$

and

$$D_\gamma = 0.55K_\gamma + 0.07K_n$$

where D_n and D_γ are neutron and gamma doses, respectively, and K_γ and K_n represent the kerma. We used the same conversion factors.

Aberration Coefficients

As already noted, the relationship between initial aberration frequency and dose, where both high- and low-LET radiations are involved, has the general form

$$Y = b + \alpha_n D_n + \alpha_\gamma D_\gamma + \beta_\gamma D_\gamma^2$$

where α_n and α_γ are the linear coefficients of asymmetrical exchange production for high-LET (neutrons in this case) and gamma rays, respectively; β_γ is the dose-squared coefficient of asymmetrical exchange production for gamma rays; and b is the spontaneous asymmetrical exchange frequency. This is the LQ-L model discussed earlier. We adopted the values of $\alpha_n = 0.008$ cell^{-1} rad^{-1}, $\alpha_\gamma = 0.00022$ cell^{-1} rad^{-1}, and $\beta_\gamma = 6.9 \times 10^{-6}$ cell^{-1} rad^{-2} for asymmetrical exchange production, selected by Randolph and Brewen from the literature, and used the values of b actually measured by Awa et al. (1978) for the unexposed control populations in each city. With these values the above expression gives the yields of asymmetrical exchange aberrations expected in lymphocytes sampled immediately after irradiation.

Conversion Factors

The Hiroshima and Nagasaki cytogenetic observations were made on material obtained in 1968 and 1969 and therefore had to be corrected for loss during the average of 23.5 years between the bombings and the sampling. Also, since the Nagasaki observations are reported only for all exchanges, estimates of the symmetrical exchange frequencies must be added to those for asymmetrical exchanges. Again, following Randolph and Brewen, we assume that $^1/_{79}$ of the original asymmetrical exchanges will be observed at 23.5 years; that, although symmetrical exchanges are probably induced in frequencies equal to those for asymmetrical exchanges, poorer ascertainment reduces their frequency to $^1/_{3.6}$ of the initial asymmetrical frequency; and that asymmetrical exchanges are not lost as a function of cell division at all. Thus the total exchange frequency at 23.5 years can be derived from the estimated initial asymmetrical exchange frequency as

$$Y_{T23.5} = \frac{Y_{A0}}{79} + \frac{Y_{A0}}{3.6}$$

where $Y_{T23.5}$ is the total exchange frequency at 23.5 years, and Y_{A0} is the initial asymmetrical exchange frequency.

One additional factor must be taken into account: the Nagasaki exchange data are reported only as frequency of cells with exchanges, whereas $Y_{T23.5}$ is the frequency of exchanges per cell. At least for the predominant gamma component of dose, we expect the aberrations to have a Poisson distribution among the cells. The assumption that this distribution might still hold after 23.5 years is unproven, but it is reasonably well supported by the data of Awa et al. (1978) in their Table 5 on the average number of aberrations in cells having any aberrations at all. We therefore adopt this assumption and convert $Y_{T23.5}$ to the expected frequency of cells with exchanges, Y_{cx}, as

$$Y_{cx} = 1 - e^{-Y_{T23.5}}$$

The expected percentages of cells with any exchange that we calculated are shown in Table 3 and Fig. 2, along with the actual values observed by

TABLE 3

Percentage of Cells with Exchange Aberrations Observed, as Tabulated by Otake (1979), and Expected, as Calculated by Method Described in Text from the T65D and the LLNL Kerma, for Hiroshima and Nagasaki

Total T65D dose, rads	Observed	Cells with any exchange aberration: From T65D kerma	Cells with any exchange aberration: From LLNL kerma
		Hiroshima	
Control	0.86		
1 to 69	1.45	1.31	1.21
70 to 139	3.94	3.13	2.80
140 to 209	5.24	4.73	4.46
210 to 299	8.32	7.17	7.11
300 to 499	11.88	12.41	13.14
500 to 600	18.07	19.37	20.96
		Nagasaki	
Control	0.87		
1 to 69	1.26	1.05	0.98
70 to 139	1.28	1.93	1.46
140 to 209	1.45	3.26	2.13
210 to 299	2.21	5.55	3.40
300 to 499	4.54	10.53	6.42
500 to 600	12.01	18.73	11.35

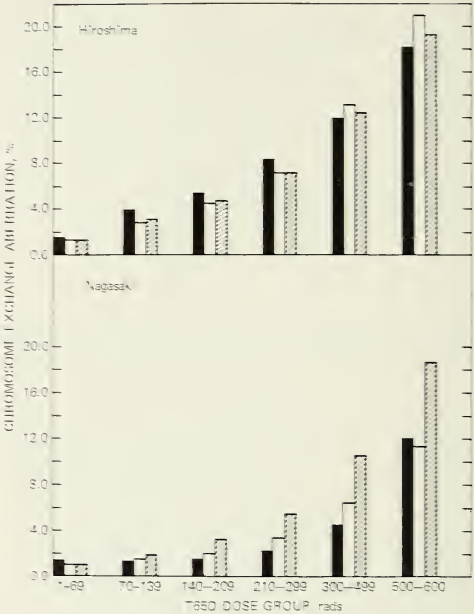

Fig. 2 Observed frequencies of cells with exchange aberrations and expected values calculated from both T65D and LLNL dose estimates. ■, observed aberration, %. □, LLNL calculated aberration, %. ▨, T65D calculated aberration, %.

Awa et al. as presented by Otake (1979). For Hiroshima the agreement is generally remarkably good between the observed and the expected values calculated for either the T65D or the LLNL kerma, but for Nagasaki the agreement is much better for the expected values calculated from the LLNL kerma than for those calculated from the T65D. Perhaps surprisingly, in other words, the LLNL kerma calculations make little difference for the Hiroshima data but result in a substantially better agreement for the Nagasaki data.

Obviously, the lack of notable effect from the substantial reduction in neutron kerma values for Hiroshima results from the compensatory increases in gamma kerma values. We emphasize, however, that the coefficients of asymmetrical exchange aberration production we used are empirically determined and are totally independent of the Hiroshima and Nagasaki observations. Furthermore, the "right" RBE for the neutron component of dose is also empirically derived from the experimental evidence; it is, of course, the "ultimate" RBE given by the ratio of the α_n to α_γ coefficients of asymmetrical exchange aberration production, or 0.008 : 0.00022 = 36.4. Thus the substantial agreement of the calculated residual exchange aberration frequencies with those actually observed, particularly at Hiroshima, demonstrates that both sets of kerma estimates are reasonable, the LLNL more so than the T65D at Nagasaki.

Apparently, then, even the somatic chromosome aberration data do not, in fact, allow any definitive choice to be made between the two dosimetries or, more particularly, offer any clue regarding the relative magnitude of neutron kermas at Hiroshima. The LLNL kerma estimates do appear to bring the somatic aberration data for the two cities into closer agreement; however, until new shielding factors are calculated and the individual tissue dose estimates revised, this is about all that can be said. Even this may be misleading since it is entirely possible to choose a set of aberration coefficients from within the ranges of estimates in the literature cited by Randolph and Brewen which bring the calculated curves for the two cities into excellent agreement for either the T65D or the LLNL kerma estimates.

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Sensitivity of Hiroshima and Nagasaki Epidemiologic Inferences to Dosimetric Parameters

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ABSTRACT

In this paper the influence that various possible values of physical dosimetric parameters can have on radiobiological interpretations of Hiroshima and Nagasaki epidemiologic data is analyzed. The physical parameters studied, which include yields of the weapons devices, neutron and gamma-ray outputs, and slopes of the dose-vs.-distance functions, are allowed to vary over reasonable ranges, and the resulting effects on a representative biological end point are evaluated. The end point used is the radiation-induced chromosome aberrations in blood cells of atom-bomb survivors. Although this is statistically perhaps the strongest set of biomedical observations available for the purpose, it is used in this paper simply as an indicator end point for exploring the biological consequences of varying the physical parameters.

Neutron RBE's (relative biological effectiveness values) calculated from the resulting dose–response relationships are found to be most sensitive to variations in device yield, with a sensitivity ratio (SR) of 1.2 (12% change resulting from 10% parameter change). The RBE's are also very sensitive to neutron output alone (SR = 0.7) of the Hiroshima device. They are least sensitive to gamma-ray output (SR = 0.4) of the Hiroshima device. Gamma-ray risk coefficients, which depend only on Nagasaki data, are inversely proportional to the gamma-ray output (and device yield) of the Nagasaki device.

On the basis of the assumption that neutrons could not have been protective, results from this analysis suggest limits on certain physical parameters—device yields and gamma-ray outputs for both cities. No such limits, however, are found for reasonable values of Hiroshima neutron output, and this parameter has the potential for strongly influencing inferences regarding neutron RBE.

Radiation biology and radiation epidemiology can play significant roles in the evaluation of past and present dosimetry at Hiroshima and Nagasaki as well as in the planning of projected dosimetric work. These disciplines can contribute to setting goals for statistical confidence limits of the relevant physical data, to defining zones of reasonable dosimetric outcome, and perhaps to making choices among physical alternatives. They may also clarify some of the ongoing and confused public debate about the impact of recent changes in the dosimetry on issues of radiation standards and regulatory policy.

The new radiation dose estimates for Hiroshima and Nagasaki (Loewe and Mendelsohn, 1981; Kerr, 1981) differ significantly from the previously accepted T65D estimates (Auxier et al., 1966; Auxier, 1977), and a number of investigators are actively engaged in further dosimetric work aimed at establishing with acceptable precision what the doses were. It is especially profitable at this stage, therefore, while further dosimetry is being planned and pursued, to examine systematically both the magnitude and range of effects that various possible values of physical dosimetric parameters can have on radiobiological interpretations of the data from atom-bomb survivors. Such an examination is made here in an attempt to identify the parameters in need of greatest precision and to provide a clearer perspective on the relationship between the physics and the biology.

Chromosome aberrations enumerated in blood lymphocytes of persons exposed at Hiroshima and Nagasaki were selected as the radiation-effect end point for this analysis. The data for this particular end point are especially extensive (Awa et al., 1978) and constitute probably the most statistically robust set of observations available. Furthermore, chromosome aberrations are biologically important: they indicate damage to genetic structures and may be involved in carcinogenesis. It should be emphasized, however, that for present purposes this data set was selected simply as a representative *model* biological end point. We are concerned here not with any specific dose–response relationship but with elucidating how such relationships depend on, and vary with, dosimetric parameter values.

The physical parameters studied include yields of the two weapons devices, neutron output of the Hiroshima device, slope of the Hiroshima neutron dose-vs.-distance function, gamma-ray outputs, and slope of the gamma-ray dose-vs.-distance function. Neutron relative biological effectiveness (RBE) values and gamma-ray risk coefficients have been calculated from the biological data for the various parametric assumptions and have been compared with corresponding data in the radiobiological literature.

METHODS

Biological End Point and Curve Fitting

Data for chromosomal exchanges are from the 1978 report of Awa and co-workers on radiation-induced chromosome aberrations in atom-bomb survivors. In this study our attention is confined to exchanges since they are least susceptible to uncertainties; data for other aberrations recorded by Awa et al. (1978) have not been included in this analysis.

For fitting basic dose–response curves to the biological data, linear-quadratic least-squares best fits have been used, with data points weighted by $1/(SD)^2$, where SD (standard deviation) = 100 × (number of cells with exchanges)$^{1/2}$ per number of cells examined. Additional SD's reflecting interpersonal differences were not given by Awa et al. (1978). For both Hiroshima and Nagasaki, only the lower portions of the curves have been used for analysis—the lower four data points for Hiroshima and the lower six points for Nagasaki, as shown in Fig. 1 by solid curves. Above these fitted regions inflections occur as the curves change from positive to negative curvature (presumably reflecting cell-killing effects). The higher data points, eye-fitted with dashed curves in Fig. 1, have not been used in the analysis. Confidence limits for the biological data, except as used in curve fitting, have not been considered here, since they are not relevant to the analysis of effects of dosimetric parameter variation.

Reference Dosimetric Parameters

The values for physical dosimetric parameters given by Loewe and Mendelsohn (1981) have been taken here, quite arbitrarily, as reference values for the independent variables used in the analysis. This particular

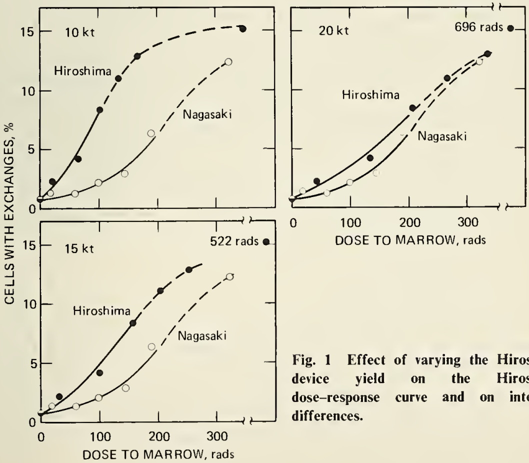


Fig. 1 Effect of varying the Hiroshima device yield on the Hiroshima dose–response curve and on intercity differences.

reference selection was for convenience only; other estimates, such as those of Auxier et al. (1966), could serve equally well.

Transmission Factors for Japanese Houses and the Human Body

Although questions concerning transmission-factor values are not directly relevant to our principal concern here, they are important to relating neutron RBE's from the Japanese data to those found experimentally in the laboratory. New transmission factors determined for the reference energy spectra (Loewe and Mendelsohn, 1982) have not yet been generally agreed on and are currently being investigated. However, for this analysis we have derived approximate values so as to estimate the impact that the new spectra could have on the total transmission factors (i.e., Japanese houses and the human body) used here. New values for Japanese houses estimated by Marcum (1981) are shown in Table 1. For the human body we derived transmission factors by applying published values (Jones, 1977; Kerr, 1979) to estimated averages of the reference gamma-ray energy spectra for prompt, fission-product, and neutron-capture gamma rays. For neutrons we assumed that T65D body transmission factors remained unchanged since Marcum (1981) found for Japanese houses (mostly wood frame) that no significant changes had been indicated. Total transmission factors (for houses plus the human body) for converting free-in-air tissue kerma to bone-marrow dose by this method will not be greatly different from those of T65D, as illustrated in Table 1.

Hence, for this investigation, dose to bone marrow (chosen as reasonably representative for sites of lymphocytic stem cells) was calculated from the reference free-in-air tissue kerma by using attenuation factors derived for T65D spectra, as given by Milton and Shohoji (1968) for Japanese houses and by Kerr (1979) for average Japanese anatomical features. However, mean values for each city, as given by Milton and Shohoji (1968), were not used; rather, more range-specific values were obtained from their data by taking into account the regional differences in shielding described by them for various distances.

Neutron RBE Calculation

The RBE values for Hiroshima neutrons were determined by the method of Rossi and Mays (1978). The principle of this method is shown in Table 2. For the gamma-ray component of each Hiroshima data point, an identical gamma-ray dose, together with its associated effect and (small) neutron dose component, is obtained by interpolation from the fitted Nagasaki dose–response curve (which represents nearly pure gamma rays). The Nagasaki values are then subtracted from the Hiroshima

TABLE 1

Transmission Factors for T65D Compared with Those Estimated for Reference Doses

	Hiroshima				Nagasaki			
	T65D value		Reference value*		T65D value		Reference value*	
	Neutrons	Gamma rays	Neutrons	Gamma rays	Neutrons	Gamma rays	Neutrons	Gamma rays
Houses	0.32	0.90	~0.35†	0.55†	0.35†	0.81†	~0.35†	0.50†
Body‡	0.28	0.56	~0.28	~0.89	0.28	0.56	~0.28	~0.89
Total transmission factors	0.09	0.50	~0.10	~0.49	0.10	0.45	~0.10	~0.45

*Derived for the reference spectra as described in text.

†From Marcum, 1981.

‡Shielding of bone marrow by body tissue.

TABLE 2

RBE Analysis for Radiation-Induced Chromosomal Exchanges by Using Reference Doses

Hiroshima			Nagasaki			Residual Hiroshima		
Gamma-ray dose, rads	Neutron dose, rads	Net effect*	Gamma-ray dose, rads	Neutron dose, rads	Net effect*	Gamma-ray dose, rads	Neutron dose, rads	Net effect*
0	0	0	0	0	0	0	0	0
32	0.3	1.3	32	0.05	0.1	0	0.25	1.2
96	1.7	3.3	96	0.25	1.1	0	1.45	2.2
152	3.4	7.5	152	0.56	3.0	0	2.84	4.5

*Percentage of cells with chromosomal exchanges; control values (y-intercepts of fitted curves) subtracted.

values, leaving only residual Hiroshima neutron dose and its corresponding residual effect. From these residual values a neutron dose–response curve is constructed. Neutron RBE values are then obtained from fitted dose–response curves (assumed to be linear for Hiroshima neutrons and linear quadratic for the Nagasaki radiation) by taking the ratios of equal-effect doses.

RADIOBIOLOGICAL CONSEQUENCES OF VARYING DOSIMETRIC PARAMETERS

Effects on Neutron RBE

Yield of Hiroshima Device

To examine the effect on neutron RBE of changing the assumed values of the yield of the Hiroshima device, we allowed the yield to range from 10 to 25 kt, encompassing both 15 kt, the value recently proposed by Loewe and Mendelsohn (1981), and 12.5 kt, the value used in the T65D estimates (Auxier et al., 1966; Auxier, 1977) and also proposed by Kerr (1981). In Fig. 1, dose–response curves for chromosomal-exchange aberrations vs. total radiation dose to bone marrow are shown for 10, 15, and 20 kt. At 10 kt the Hiroshima and Nagasaki curves differ greatly from each other. Their divergence is less at a device yield of 15 kt. The Hiroshima curve continues to move to the right as yield increases further, and the two curves become almost indistinguishable at 20 kt.

From such curves dose–response relationships for neutrons were derived as described in the preceding section. A set of such relationships is shown in Fig. 2 for Hiroshima yields of 10 to 25 kt. They are reasonably linear, particularly at lower kiloton values [linearity is expected for neutrons (Lloyd et al., 1976)]. At 25 kt, however, there are difficulties: not only is there nonlinearity but also the function is negative, which is biologically absurd. From the radiobiological relationships, then, a value of about 20 kt appears to be an upper limit of plausible Hiroshima yield.

The neutron dose–response relationships, linearly fitted, were used to derive corresponding neutron RBE values, and the systematic dependence of RBE on Hiroshima yield is shown in Fig. 3. The function is quite steep for small neutron doses, the RBE rising as relative Hiroshima yield decreases. The question then is: Are any of these RBE values radiobiologically plausible? This is addressed in Fig. 4, where neutron RBE's for Hiroshima yields of 10, 15, and 20 kt are displayed as functions of neutron dose in a diagram that also shows, for comparison, laboratory results from four radiobiological end points for which extensive experimental data were

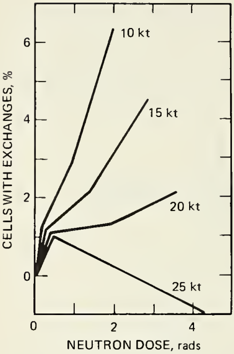


Fig. 2 Neutron dose–response curves for various Hiroshima device yields.

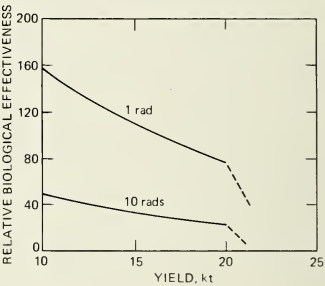


Fig. 3 Neutron relative biological effectiveness (RBE) as a function of Hiroshima device yield, shown for neutron doses of 1 rad and 10 rads. Dashed portions of curves represent device yields giving negative neutron dose–response functions.

available (Rossi, 1980), including a malignancy (in the rat), mutations (in a plant), and chromosome aberrations (in human lymphocytes irradiated in vitro). As shown in Fig. 4, neutron RBE's calculated from the Hiroshima–Nagasaki data were higher than those expected from the laboratory results. The atom-bomb RBE's approached the experimental RBE's as yield increased, but even at the upper limit of biologically plausible Hiroshima yield they remained above the experimentally expected values.

Yield of Nagasaki Device

The yield of the Nagasaki device was allowed to range from 17.5 to 24 kt, encompassing the generally accepted value of 22 kt (about which there is no serious debate), whereas all other parameters were held constant at the reference values. Neutron RBE's calculated for various Nagasaki yields are shown in Fig. 5, again plotted with laboratory data for comparison. The influence of the Nagasaki device yield on RBE, although opposite to that of the Hiroshima device yield (compare Figs. 4 and 5), is of similar magnitude; the values again lie well above literature values for all

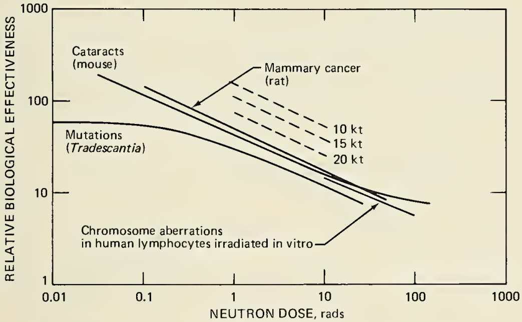


Fig. 4 Neutron relative biological effectiveness (RBE) values derived for various Hiroshima device yields (comparison with laboratory experimental values).

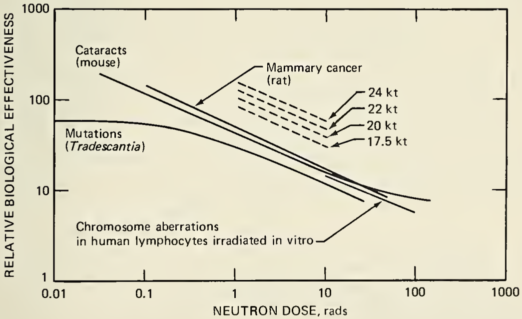


Fig. 5 Neutron relative biological effectiveness (RBE) values derived for various Nagasaki device yields (comparison with laboratory experimental values).

acceptable and reasonable yields. The data for neutron dose–response curves are not shown, but below 17.5 kt the curves become negative, which indicates a lower limit for the Nagasaki yield.

Neutron Output of Hiroshima Device

The neutron output of the Hiroshima device was allowed to range from 0.5 to 5 times the reference value; all other parameters, including the yield from the Hiroshima device, were held constant. Representative neutron dose–response curves derived from the resulting relationships are shown in Fig. 6, and the systematic dependence of RBE on Hiroshima neutron output, for representative doses of 1 rad and 10 rads, is shown in Fig. 7. For small doses the function is quite steep, especially at lower neutron outputs.

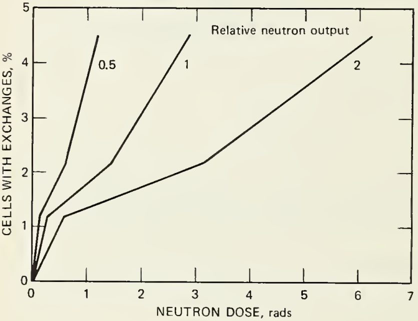


Fig. 6 Effect of relative Hiroshima neutron output on neutron dose response.

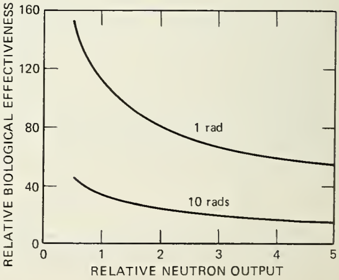


Fig. 7 Neutron relative biological effectiveness (RBE) as a function of relative neutron output, shown for neutron doses of 1 rad and 10 rads.

The overall effect of neutron output on RBE is shown in Fig. 8, where RBE in the 1- to 10-rad range of neutron dose is shown for a series of assumed neutron outputs. Interestingly, for outputs three to five times as great as the reference value (intermediate between reference and T65D), calculated RBE's lie very close to or within the range of laboratory experimental data. No biological constraints were found for any reasonable Hiroshima neutron output values.

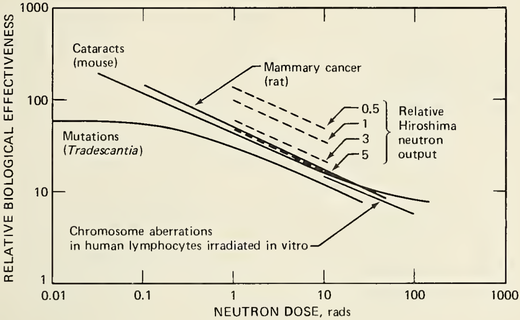


Fig. 8 Neutron RBE values derived for various relative Hiroshima neutron outputs (comparison with laboratory experimental data).

Slope of Hiroshima Neutron Dose-Vs.-Distance Function

To explore the influence of this parameter, we used two approaches. In the first, referred to as "tilt 1" and illustrated in Fig. 9, the slope of the dose-vs.-distance function was varied, all resulting curves having common origin at zero slant range (i.e., at the exploding device). In the second, referred to as "tilt 2" and illustrated in Fig. 12, the function was allowed to pivot about a common point at a slant range of interest, which allowed exploration of greater differences in slope.

Tilt 1. For tilt 1, the reference neutron dose-vs.-distance function (Loewe and Mendelsohn, 1982), shown in Fig. 9 as a solid curve, was first approximated by a straight line (dashed line 1 in Fig. 9). Then lines of common origin but of differing slope were considered (two are shown in Fig. 9, dashed and labeled 0.5 and 2). The numerical values assigned to the considered lines, e.g., 0.5, 1, and 2 in Fig. 9, refer not to the slopes themselves but to relative neutron dose (compared with the reference value

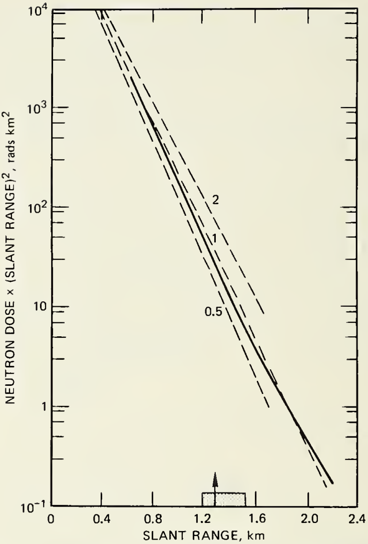


Fig. 9 Tilt 1. The solid line is the reference function for Hiroshima (Loewe and Mendelsohn, 1982). Line 1 (dashed) is a linear approximation to it; lines 0.5 and 2 represent one-half and two times the reference dose at 1.28 km (arrow). The shaded area between 1.19 and 1.54 km indicates the range span used in the present analysis.

on the solid curve) at a particular (but arbitrary) slant range of interest, namely, 1.28 km, corresponding to the third data point of the fitted Hiroshima dose–response curves in Fig. 1.

Neutron dose–response curves derived for relative tilt 1 of 0.5 to 2 are shown in Fig. 10. Comparison of Figs. 6 and 10 shows that the tilt-1 approach gives results very similar to those for variations in neutron output. This is a reflection of the slope similarity of the lines in Fig. 9. Over the limited slant range of interest (indicated on the abscissa in Fig. 9), lines 0.5, 1, and 2 do not appear for practical purposes very different from parallel. The resulting similarity in results is graphically shown in Fig. 11, where neutron dose–response curves for various neutron outputs and for various tilt-1 values are plotted together. The effects of variations in tilt 1

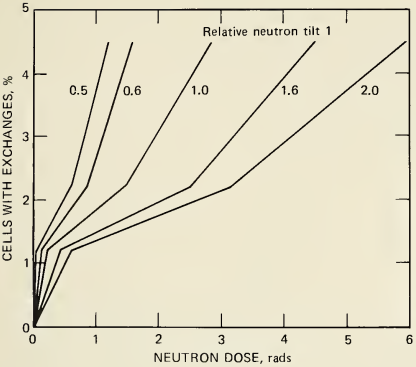


Fig. 10 Effect of relative Hiroshima neutron tilt 1 on neutron dose response.

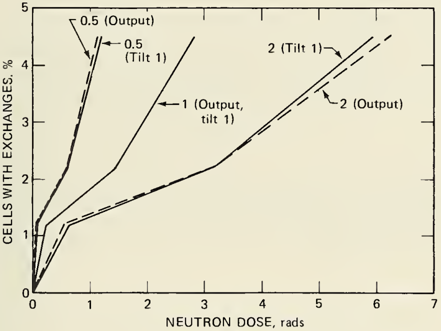


Fig. 11 Comparison of the effects of relative Hiroshima neutron tilt 1 and neutron output on neutron dose response.

on neutron RBE are quite similar to those shown in Figs. 7 and 8 for variations in Hiroshima neutron output.

Tilt 2. For tilt 2 the reference function, shown in Fig. 12 as a solid curve, was again first approximated by a straight line (dashed line 1 in Fig. 12). Then lines of significantly differing slope, intersecting at a point corresponding to the middle of the biological data range (indicated on the

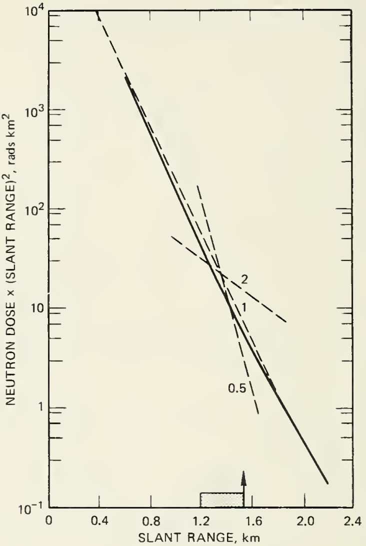


Fig. 12 Tilt 2. The solid line is the reference function for Hiroshima (Loewe and Mendelsohn, 1982). Line 1 (dashed) is a linear approximation to it; lines 0.5 and 2 represent one-half and two times the reference dose at 1.54 km (arrow). The shaded area between 1.19 and 1.54 km indicates the range span used in the present analysis.

abscissa in Fig. 12) were considered. Numerical values assigned to the lines, e.g., 0.5, 1, and 2 in Fig. 12, refer not to slopes but to relative neutron doses at the 1.54-km slant range, the distance corresponding to the second Hiroshima data point used for fitting the dose–response curves of Fig. 1.

The influence of tilt 2 on neutron RBE is summarized in Table 3. The RBE is not a strong function of tilt-2 variation; it changes only from about 150 to 100 for an unrealistically exaggerated range of relative tilt-2 values. (That this range is unrealistic is shown by neutron outputs corresponding to extrapolations, to zero slant range, of lines 0.5 and 2 of Fig. 12; they correspond, respectively, to 200 and 0.004 times the reference value, well exceeding reasonable limits.)

TABLE 3

Effect of Neutron Tilt 2 on Relative Biological Effectiveness (RBE)

Relative tilt 2	Neutron RBE at 1 rad	Relative neutron output
0.5	154	200
0.8	130	6
1.0	111	1
1.3	102	0.06
2.0	92	0.004

Gamma-Ray Output of Hiroshima Device

Figure 13 shows a group of neutron dose–response curves derived from relationships for various assumed gamma-ray outputs of the Hiroshima device. The RBE dependence on this parameter is shown in Fig. 14 for representative neutron doses of 1 rad and 10 rads, and in Fig. 15 the RBE's for various assumed Hiroshima gamma-ray outputs are compared with laboratory radiobiological results. As shown in Figs. 14 and 15, the RBE is only weakly influenced by variations in Hiroshima gamma-ray output. For relative gamma-ray outputs exceeding 1.25, the neutron dose–response curve becomes biologically meaningless.

Gamma-Ray Output of Nagasaki Device

This parameter affects RBE in the same way as the yield of the Nagasaki device.

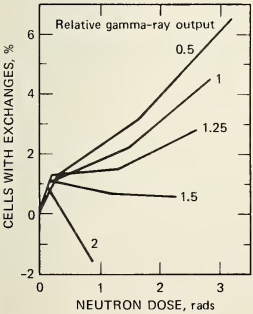


Fig. 13 Effect of relative Hiroshima gamma-ray output on neutron dose response.

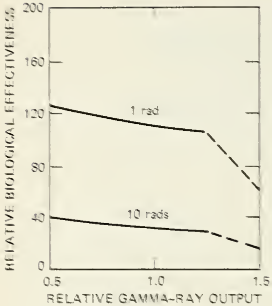


Fig. 14 Neutron relative biological effectiveness (RBE) as a function of Hiroshima gamma-ray output shown for neutron doses of 1 rad and 10 rads. Dashed portions of curves represent gamma-ray outputs giving negative neutron dose–response functions.

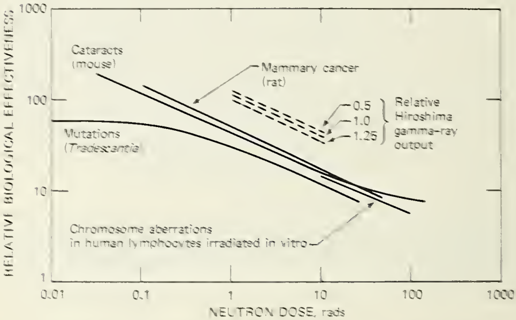


Fig. 15 Neutron RBE values derived for various relative Hiroshima gamma-ray outputs (comparison with laboratory experimental data).

Slope of Hiroshima Gamma-Ray Dose-Vs.-Distance Function

As in the analysis for effects of Hiroshima neutron tilt 1, the slope of the Hiroshima gamma-ray dose-vs.-distance function was allowed to vary so that gamma-ray doses at a particular slant range of interest (1.28 km, corresponding to the third data point of the fitted Hiroshima dose–response curves of Fig. 1) were 0.5 to 1.6 times as great as the reference value. Neutron dose–response curves were then derived for various tilts (Fig. 16). They suggest an upper limit of gamma-ray tilt not greatly

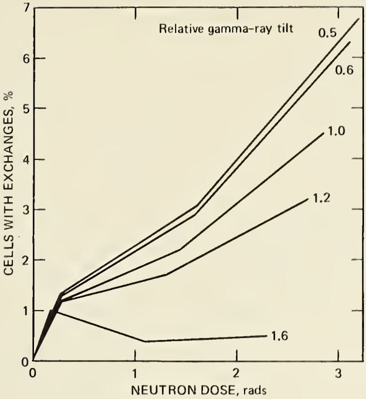


Fig. 16 Effect of relative Hiroshima gamma-ray tilt on neutron dose response.

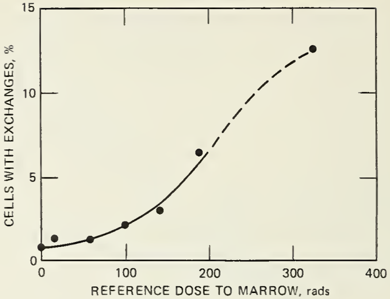
exceeding 1.2 times as great as the reference value. Neutron RBE is only weakly dependent on Hiroshima gamma-ray tilt, the effect of which is similar to that of Hiroshima gamma-ray output (compare Figs. 13 and 16).

Effects on Gamma-Ray Risk Coefficient

Gamma-Ray Output of Nagasaki Device

Because the radiation field at Hiroshima was a mixed one with a significant neutron component (Loewe and Mendelsohn, 1981; Kerr, 1981; Auxier, 1977), the only reliable basis from the atom-bomb data for inferences concerning gamma-ray effectiveness is provided by the Nagasaki data. [The neutron dose to bone marrow at Nagasaki was less than about 0.3% of the total dose at slant ranges of most interest to radioepidemiology (Loewe and Mendelsohn, 1981).] Hence gamma-ray risk coefficients inferred from the atom-bomb experience in Japan depend almost solely on the Nagasaki gamma-ray output.

The effects of gamma-ray output variations on the dose–response curve are readily visualized from Fig. 17 by allowing values on the dose axis to be fractions and multiples of the reference values. Shown in Fig. 17 are the risk coefficients for chromosomal exchanges, arbitrarily calculated for 100 rads (they are lower at lower dose) corresponding to gamma-ray out-



Relative gamma-ray output	Risk coefficient* (at 100 rads)
0.5	2.4×10^{-2}
1.0	1.2×10^{-2}
2.0	0.6×10^{-2}

*Percentage of cells with exchanges per rad.

Fig. 17 Effect of relative Nagasaki gamma-ray output on the gamma-ray risk coefficient for chromosomal exchanges. The relative outputs represent 0.5 and 2 times the reference value.

puts 0.5, 1, and 2 times as great as the reference value. The risk coefficient is simply inversely proportional to the Nagasaki gamma-ray output. It should be noted that the risk coefficient derived with the reference dose values is compatible, within a factor of 2, with experimental results from human lymphocytes irradiated in vitro (Lloyd et al., 1975).

CONCLUSIONS

The power that dosimetric parameters have relative to one another in affecting calculated neutron RBE is illustrated in Fig. 18. A curve for RBE vs. relative Nagasaki yield is not shown; it is equally as steep as that for relative Hiroshima yield but is of opposite slope. The next most powerful parameter after the device yields is the neutron dose at Hiroshima, whether from neutron output or from tilt 1 or tilt 2. Least powerful is the Hiroshima gamma-ray dose, whether it is from gamma-ray output or tilt.

For simplification of comparisons, the sensitivity of calculated RBE to changes in each of the parameters can be expressed as a sensitivity ratio (SR),

$$\mathrm{SR} = \frac{\text{Percentage change in RBE}}{\text{10\% Change in parameter value}}$$

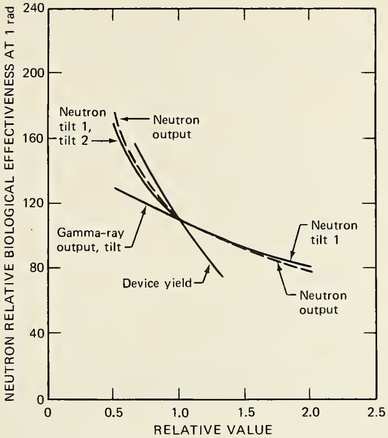


Fig. 18 **A composite of Hiroshima dose-parameter effects on neutron relative biological effectiveness (RBE). (A relative value of 1.0 is equivalent to the reference value.)**

The parameters are ranked, together with their associated SR's, in Table 4.

Although this analysis was done by varying one physical parameter at a time, changes in combinations of parameters should have roughly additive effects as well as roughly additive constraints. For example, increasing the yield of both devices by the same factor will have no effect on RBE, whereas an increment (from the reference value) of 16% to Hiroshima yield and a decrement of 16% to Nagasaki yield should be equivalent to a 32% increment to Hiroshima yield and would result in a 35% reduction in neutron RBE (approximately the biologically limiting value for this physical parameter and model end point; see Fig. 3).

Although the concept of gamma-ray risk coefficient may not seem to apply to the end point used here (i.e., chromosomal aberrations) in quite the same way that it does to cancer induction, the effects of dosimetric parameter variation on risk coefficient will be exactly the same for other end points, including carcinogenesis. All gamma-ray risk coefficients derived from the atom-bomb data will be inversely proportional to the Nagasaki gamma-ray output (and to the Nagasaki yield, which determines the gamma-ray output).

TABLE 4

Relative Sensitivity of Neutron Relative Biological Effectiveness (RBE) to Changes in Physical Parameters

Physical parameter	Sensitivity ratio (SR)*
Hiroshima device yield	1.2
Nagasaki device yield	1.2
Nagasaki gamma-ray output	1.2
Hiroshima neutron output	0.7
Hiroshima neutron tilt 1	0.6
Hiroshima neutron tilt 2	0.6
Hiroshima gamma-ray output	0.4
Hiroshima gamma-ray tilt	0.4

$$^{*}\text{SR} = \frac{\text{Percentage change in RBE}}{\text{10\% Change in parameter value}}$$

In this analysis we have evaluated the effects that changes in physical dosimetric parameters can have on biomedical inferences. In general, we have found (1) that the radiobiology can be used both qualitatively and quantitatively to help establish reasonable limits on physical parameter values and (2) that the parameters can be ranked according to their power in affecting neutron RBE.

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DISCUSSION

Woolson: Your study concerns the variation in neutron RBE (relative biological effectiveness) as a function of the variation in the yield assigned to the Hiroshima and Nagasaki weapons. The papers presented at this conference seem to indicate that the yield uncertainty at Hiroshima is around 30% and that the uncertainty for Nagasaki is a lot less. Some of us believe that there may be as much as a factor of 2 bias in the gamma-ray dose to survivors in *both* cities. How would this bias affect the neutron RBE?

M. Mendelsohn: A 30% uncertainty in overall yield at Hiroshima would translate by using our method into a 32% uncertainty in RBE. As yield increases, RBE decreases. The effect of a change of a factor of 2 in transmission factor for gamma rays would depend on the assumptions (e.g., the tilt-1 or tilt-2 model). We have not estimated such effects by using the magnitude of transmission factor per se, but this could easily be done. I would predict that the results will depend on gamma dose in the center of the range of interest. According to our calculation, a halving of the gamma dose at Hiroshima would raise the RBE by 20%. Our upper limit for a tolerable increase in gamma dose is 20%, and this would decrease the RBE by 8%.

Woolson: For Nagasaki as well?

M. Mendelsohn: The 10% uncertainty in overall yield at Nagasaki translates into a 12% effect on RBE. This effect is opposite in direction to the Hiroshima effect, so that a systematic bias moving both yields the same percent in the same direction would have no effect on RBE. A systematic bias in gamma-ray transmission is too difficult for me to estimate without having specific assumptions and doing the calculations.

B. R. Scott: The procedure that you used to generate RBE's seems to be based on the assumption of no synergistic interaction between neutrons and gamma rays. Experimental data exist which suggest a synergistic interaction. When you subtract the gamma-ray contribution from the Hiroshima curve without accounting for the potential synergism, it seems you can only overestimate the neutron RBE. That might be why your curves are higher.

M. Mendelsohn: That's an interesting point. I was not aware of synergism between these two radiation effects. Do any radiation biologists want to comment on that?

Bender: There is information on interaction, not synergism, between neutron-induced breaks and gamma-ray-induced breaks. I am unaware, however, of any chromosome-aberration data which suggest a positive synergism which is more than the simple interaction expected from an essentially linear generation of breaks per unit dose for neutrons and an essentially dose-squared generation per unit dose for gammas.

M. Mendelsohn: You mean the dose scales can be added?

Bender: It isn't the dose scales, because the kinetics are different. It depends on where you are on the dose scale. But the data can be unscrambled; as I recall, the literature is fairly extensive. Am I correct that your analysis is based on certain dose–effect kinetics for neutrons—ill-defined here but for neutrons generally—and for gamma rays?

M. Mendelsohn: Yes, the analysis is based on a linear dose response for neutrons and a linear-quadratic dose response for gamma rays.

Bender: How big is the linear term in the linear quadratic? This is, it seems to me, what is generating your RBE's at low dose. Do you see my point?

M. Mendelsohn: Yes, except that the gamma doses are not low. Remember, these are iso effects with a neutron dose of 1 rad and a gamma dose of around 100 rads.

Bender: But your analysis is still RBE dependent. The analysis was made with the data accumulated about 23 years after the explosion, and we don't know what that time interval has done to the dose–effect kinetics. We do know, in a rough way, what it has done to the yields. I have mentioned this already, but perhaps Mac Randolph should say it himself: there is another approach to this problem, that used by Randolph and Brewen (1980), which implies that maybe the data aren't as bad as suggested by the kind of analysis you have given. Randolph and Brewen used the dose–effect kinetics and the values of the coefficients for in vitro prompt induction of chromosome aberrations and data from the literature about the loss of aberrations, which is a function of time, by using the T65D kermas for the two classes of exchange aberrations (symmetrical and asymmetrical) to regenerate the aberration yields they would have expected.

M. Mendelsohn: They extrapolated back to time zero.

Bender: Then, when they plotted the dose that would give that aberration yield against the actual kerma, they got essentially a straight line. If everything were perfect, the slope of the line relating the doses calculated from dosimetry and from aberrations would be 45°. The line obtained has a slope less than 45°, depending on the fitting and on the intercept. The line is generally too high at the low doses and too low at the high doses, but not by much. This means that, because the RBE consideration is in a way built into their original calculations, their RBE information (which I think averages about 40 for the "ultimate" RBE) is not very far off.

M. Mendelsohn: Will the change in dosimetry affect that?

Bender: I think it will. The new gamma estimates will influence it somewhat, but the degree to which they will be influenced by the shielding factors has to be addressed. I think that the unshielded gamma kermas at Hiroshima go up at the lowest doses by factors of about 4 and at the highest doses by factors of only about 2, which should skew the curve more toward 45°; but shielding revisions could make a major difference.

Straume: The Randolph and Brewen analysis, which used chromosome aberrations as a biological dosimeter, was able to predict the T65 dose only to within a factor of 2. This is about equal to the proposed changes in total dose, and therefore the Randolph and Brewen work will probably not be very helpful in distinguishing between the two sets of doses. We also have RBE's of only about a factor of 2 above the RBE that would result from the same type of analysis that uses T65D values.

Bender: That is true—yours is a bit more than a factor of 2, in general. It does not disturb me that the RBE is high. I find it impressive that, if you use a measured value of RBE to regenerate effects, the results are not far off. The best measurements of ultimate RBE's are for chromosome aberrations and for mutations in the pink stamen hairs of *Tradescantia.* I can't remember the absolute numbers.

M. Mendelsohn: From our figure estimate we judge the RBE for *Tradescantia* at 1 rad to be around 40. The response eventually reaches a plateau at an RBE of about 60.

Bender: The problem is that the linear dose–effect curve term for the gammas does not extrapolate to zero or anywhere near it. But some of the pink-stamen-hair mutation experiments were done by reducing the gamma dose rates until practically no more change was seen. That defines the alpha slope; the ratio of gamma and neutron alpha slopes gives an RBE of about 80 or 70. The data of Neary et al. (1963) come close, that is, an RBE of 100 perhaps; and those may be the best data we could have. The point is, that is not for a 1-rad value only; it also holds for values of 0.1, 0.01, and so forth.

M. Mendelsohn: I agree in principle but would reemphasize that these limiting effects occur at doses that are lower than the data we have for Hiroshima and Nagasaki. Dr. Bender is focusing on the underlying biology of the end point we used. One could also focus on the statistics, or on the epidemiology (which leads back to sampling from the two cities and to the kind of work Dr. Radford has been doing), or on the dosimetry. We do not hold up our work as a final answer but simply as a tool to show the relationship between the physical properties and the inferences that can be drawn from any set of biological properties. Sooner or later any biological response will show the kind of constraints we have discussed. It will show its direction of change in relationship to changing the physical properties and, at least roughly, its sensitivity to the physical properties.

Jablon: One of my fondly held beliefs has been proved wrong. It was that no physicist but all biologists always put confidence intervals on their results. You mentioned statistics; I think many of the points you've been showing would have very large error bars. Related to that is a problem with the data on complex chromosomal aberrations, which clearly are becoming one of the touchstones against which to judge the validity of any proposed dosimetry. For instance, one huge error in most of the published analyses of the chromosome-aberration data is as follows. For a given dose interval, so many thousands of cells were examined and so many aberrations were found, and then the counts were treated as though they were observations from a binomial or possibly from a Poisson distribution. However, that was not in fact the sampling situation at all; in many of the dose intervals these very large numbers of cells came from five or six or seven individuals, and that introduces a lot of individual variation. Ross Prentice and two of his colleagues who have just visited the RERF (Radiation Effects Research Foundation) have looked into this and found the variance between individuals to be about four times that expected for simple binomial variation. So there's a lot more variability in chromosome data than anybody has realized.

M. Mendelsohn: That is an excellent point, and it certainly fits my own experience with similar kinds of data where variation between animals can be three to four times as large as Poisson errors from samples within any one animal. As for the statistics, I didn't put any on the slides, to avoid getting lost in detail, but I essentially concluded with a statistical summary. The dynamics are the same regardless of the statistics, even though the credibility may not be the same.

Kaul: I appreciate that the temptation to scale new dosimetry to individual dose and to do these kinds of sensitivity analyses is well-nigh irresistible, and I am certainly not in a position to question the methods being demonstrated here. However, I claim that drawing conclusions from any of the data to which the methods have been applied or from the results stated here is exceedingly premature on the following basis. The data are arranged in cohorts by dose, which means that a man at 2000 m in the open is grouped with a man at 1000 m inside a building. I imagine that, when the final analysis is done, there will be cohort-hopping the like of which nobody has even begun to guess and that the ratios of neutrons to gammas within given cohorts will be of substantial interest. Thus, whereas some of these sensitivity approaches are interesting from the standpoint of the methods used and because they can offer an insight into how sensitive our results are after we have them, I would point out that we don't have them yet. Therefore the sensitivity methods must remain methods to be used after we have some results.

M. Mendelsohn: I couldn't have said that better, except that I think the sensitivity analyses have some use a priori in planning the dosimetric analyses.

Levin: Some years ago Seymour Jablon evaluated RBE's for the ABCC (Atomic Bomb Casualty Commission) by using a number of biological end points in a very straightforward way. He simply took the gammas and k times the neutrons, and he changed the value of k until he got the Hiroshima and the Nagasaki data to match. The highest RBE value was five or six, and one of the end points was leukemia.

Jablon: Yes.

Levin: Even though I'm a biological statistician, I don't understand the method you used for arriving at RBE. How can you come up with an

RBE of 100, when Seymour, whose methods I understand and who has worked with these data for years, comes up with six?

Jablon: I used a very crude visual method that was dominated by high doses; so what I got was estimates entirely dominated by 200- to 300-rad gamma doses.

M. Mendelsohn: I would guess the two methods should give the same result if the data points were weighted the same way.

Bond: The point here is exactly what Mike Bender has been stressing, that one gets these very high RBE's only if one compares the low-dose linear component of the low-LET quadratic with the (linear) high-LET curve. Seymour Jablon was using the entire low-LET curve—linear plus the quadratic component—and he said that the RBE was strongly dominated by the higher doses. Therefore the RBE was relatively low. Thus one sees the lower RBE's only at high doses and dose rates, and these contrast sharply with the value of 50, quoted here, which pertains strictly to a comparison of the linear terms.

M. Mendelsohn: If you remember nothing else from this presentation, please remember that neutron RBE is a function of dose. The function is not well understood, particularly for the human. It is precisely this lack of insight into human neutron radiation biology which makes the Hiroshima and Nagasaki data so important. But whatever the functional form turns out to be, it should respond more or less as we have described it as weapons yield, neutron output, and the other dosimetric parameters for the two cities' change.

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Symposium Summary

HAROLD O. WYCKOFF
National Council on Radiation Protection and Measurements, Washington, D. C.

I find it a big job to try to summarize what has happened here in two days—almost impossible—even though I know something about what had gone on before. One of the problems is terminology. I hope that, as these papers come in and as more work is done, we will use the same words to mean the same things and will really define the terms we are using.

Another subject of concern is the accuracy and the precision with which measurements are made. We do not know the orientation of most of the survivors at the time of each bomb, but for the doses, say in the breast, it makes a difference whether the individual was facing toward the bomb or away from it. This may not be true for the ovaries, which are near the center of the body. In the past, isotropic incidence of irradiation on the individual has been assumed, and that is worth looking into to make sure it is justifiable. The rationale for such an assumption should be quite clear in anything that is published.

We have heard at this meeting that we know the yield to perhaps within 10 or 20%. Results are still being analyzed, and there may be a desire to try to push for smaller uncertainties—depending upon the uncertainty of other factors or the particular application for the resultant dose–effect relationships. Each time more accuracy is requested, the rationale for it needs to be appended. It is a question of economics, as has been mentioned.

The neutron leakage radiation will be obtained by the Los Alamos and Lawrence Livermore national laboratories, apparently by two different techniques. The details of the experiments probably cannot be given out because of classification. However, we hope that it will be possible to give the results of calculations and of simulated experiments. At least this kind of comparison is necessary as a rationale for acceptance of the data.

For the neutron kerma, in terms of the old T65D it was assumed that the spectrum was an equilibrium spectrum because the various threshold detectors gave parallel lines on the usual plot. Actually the lines are not very parallel, and I think this means that the threshold detector method is not a very sensitive method of indicating equilibrium. In my opinion—and you may disagree—we cannot use that as the criterion for acceptance of the T65D data for neutrons.

For the gamma kerma, apparently we find a fair bit of agreement between the two laboratories. This is to be expected because they are using essentially the same code and also the same leakage, which is another parameter that has to be included. Still another parameter is the cross sections, and it disturbs me that different sets of cross sections seem now to give very similar values for kerma vs. distance. So, how do you know which set is the correct one? It disturbs me even more for somebody to say that one can use these data to get the cross sections—it never occurred to me that anybody would. Certainly the cross sections for the interactions would have to be obtained by other experiments and then used in the kerma calculations.

Since the calculations depend so much on a single method, we must insist on experimental verification of the results. This must be done by mocking up or by using all the available data on kerma vs. distance from other types of shots or experiments. We hope that, when the proceedings of this symposium come out, we will have such a comparison and will have a feel as to whether or not the agreement is good.

A fair amount of the discussion here concerned the structural shielding. Most of this had to do with fairly light structures, where the transmissions were pretty high. That encompasses most of the survivors but not all of them. We must make sure that heavy structures get equally detailed treatment because certainly the number of survivors in such structures is not zero. They probably provide a useful set of data, perhaps with different neutron : gamma ratios, for rounding out the picture for the two types of structures.

The other problem is the depth–dose problem. One must be sure that one is calculating the proper attenuation: is it for isotropic incidence of radiation or for monodirectional? We need to review what is available about the orientation of the people during the bomb blast.

That briefly covers what I got out of this meeting. When the book comes out, I, like you, will have to consider it further before I can arrive at any conclusions as to where we stand now.

DISCUSSION

Loewe: You said there was basically one calculation that we used. That is an oversimplification because we made extensive Monte Carlo calculations to validate our discrete-ordinate calculations, and one kind of calculation tends to complement the other.

Wyckoff: I agree that this may be an oversimplification, but one cannot assume that the calculations are correct even if the methods agree, because both methods used by scientists at LLNL (Lawrence Livermore National Laboratory) use the same cross sections. At one time there was said to be a difference between the results from ORNL (Oak Ridge National Laboratory) and from LLNL, and this was attributed to differences in cross sections.

Auxier: It may not have been mentioned here, but the orientation relative to the bomb ground zero is included in the shielding histories of essentially all the survivors. The exception comprises those few people beyond 1600 m in Hiroshima for whom some grouping was done. We have the shielding histories, and anybody is welcome to look at them.

Eisenhauer: I would like to call on Dr. Thiessen and Dr. Auton before we open the general discussion.

Thiessen: As I explained in my introduction, we are of course very much interested in potential biological implications of the new data, but at this workshop our primary interest is to define the problems in the field of dosimetry. I hope that during this closing discussion we can address the following questions: What are the agreements and the disagreements? Are they resolvable, or must we agree to disagree? Do the agreements and/or disagreements concern the data sets themselves or the assumptions? Are they objective or subjective? Are there gaps in the dosimetry that have not yet been adequately addressed—loose ends that need to be tightened? What are the directions for further research? I think we are not yet ready for complete consolidation of the data base that we have. The major emphasis should be on the identification of gaps and disagreements. What I hope for, but am sure cannot be built up in two hours, is some sort of a guide to the analysis of the elements going into the total plan that eventually will result in a complete revision of T65D. As has been said, some biological questions should be kept until the end. Today, however, the problem is the physics, and not the biology, related to the dose-reassessment program.

Auton: The work I have been supporting can be described in terms of a status report of a demonstration program of what might be done. In terms of further work, I think it's imperative that we have the LANL (Los Alamos National Laboratory) calculations or some two-dimensional Little Boy leakage calculations. Then we can base the spectra that start out the air transport on something more than the one-dimensional crude calculations used so far as the basis for most of the transport. I urge the people at LANL to speed up their effort as much as possible. What we really need is the energy distribution at the weapon itself. We need to mock up the weapon spectra, probably not exactly but better than we have up to now. I don't know how much better, but experts in the field can estimate that. The early fission-product gamma-ray sources certainly need more work. The SAI (Science Applications, Inc.) work described this morning shows that we are coming closer to explaining the missing correction factor of 1.6 (or 0.6, depending on how you look at it) and that we may be missing some fission-product gammas at high energies. These should be looked for in terms of the activation of the roof-tile materials or by other means. Once we have an output or leakage spectrum that we consider reliable, we need to recalculate the air-over-ground transport, starting from the beginning, to the houses themselves and then to the people. The house-shielding factors, especially for the gamma rays, need to be reevaluated, once we get the spectra at a distance. A particularly important point is that, at the Mitsubishi steel plant in Nagasaki, essentially free-in-air doses were assumed, rather than any shielding whatsoever, and this provided a good bit of the data base for the leukemia analysis, for instance. The concrete-shielded buildings, although there are few of them, are certainly very important from DNA's (Defense Nuclear Agency's) point of view because they are mostly in the high dose range, and they, too, should be studied again. Finally, I can't emphasize too much that all these transport methods and calculations need to be compared with whatever experimental data are available. The work of some of the SAI people, as well as others, in this area has been very valuable. It should be compared with data from the weapons tests, for which the leakage spectra are known, and also with the roof-tile measurements and the sulfur and the cobalt activation results. I suspect, from my naive point of view, we won't know the yield of the Hiroshima bomb any better than we do now—a 10 or 20% uncertainty is probably the best we can get.

General Discussion

CHARLES EISENHAUER, Chairman
National Bureau of Standards, Gaithersburg, Maryland

Rossi: I believe it is quite essential to appreciate the fact that even perfect dosimetry is an inadequate basis for epidemiological conclusions wherever mixtures of neutron and gamma radiation are involved. It is meaningless to relate carcinogenic effects to the total kerma in such situations. Because of the high RBE (relative biological effectiveness) of neutrons, the effect of a given kerma must depend on the relative proportions of these radiations. This mixture may be expected to vary not only between two cities but also in a dose-dependent way within one city if only because of differences in shielding. In particular, the fraction of survivors who were heavily shielded (and therefore received a relatively larger gamma dose) is likely to be greater at higher kermas because the effects of heat and blast should have reduced the survival of unshielded individuals located near the epicenter. However, even if the relative magnitudes of neutron and gamma kerma are constant, one must consider the dependence of RBE on dose indicated by experimental and theoretical radiobiology. To meaningfully characterize the radiation exposure, one must thus make allowance for a variable RBE. In addition one must realize that—at least at higher doses—high and low linear energy transfer (LET) radiations do not act independently but in fact act synergistically [as shown by Ngo, Han, and Elkind (1977) and by R. P. Bird and F. Q. H. Ngo*] and, furthermore, one must realize that the RBE of neutrons depends on their energy (as I mentioned before). It seems hopeless to attempt to deduce the quantitative influence of all these factors from the statistically limited epi-

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*Described in M. Zaider and H. H. Rossi, The Synergistic Effects of Different Radiations, *Radiation Research*, 83: 732-739 (1980).

demiological Japanese data. It will almost certainly be necessary to make a number of assumptions based on radiobiological theory. This will certainly increase uncertainty. In view of these considerations, one would hope that in either city neutrons contributed negligibly to biological effects. We might then have a fair chance to determine at least the hazards of gamma radiation. However, the observations of M. Mendelsohn, T. Straume, and R. Dobson (in discussions presented at this meeting) would seem to make this unlikely.

Kaul: In speaking with people informally, I sense some confusion as to why we're all here. My reason may generate some controversy, and I hope that other people will give their reasons. We are not here to bless any results. Nothing said here has been cast in concrete by anyone, nor is it meant to be. We are here to bring together two groups: the radiobiologists and the epidemiologists who will be forced to live with the dosimetry results and the radiation physicists who are generating them. The members of each group understand among themselves what they are saying, but interaction has been lacking between the two groups. The radiation physicists have generated new dosimetric information, and this is the first time the two groups have had a chance to talk in an informal setting. The two groups have been brought together to identify sources of uncertainty that are important to both and thereby to provide a basis for continuation and augmentation of the work currently going on. This basis includes identifying areas which need work—complementary work—and which need some overlap of the work to define the problems involved; and it also includes estimating the time required to reach a point where people can use the data and for understanding what different calculations need to be done. We radiation physicists have the means to achieve infinite precision in our calculations but not infinite accuracy. The accuracy will be based on objective comparisons with experiments that provide good, hard data and on a subjective idea of the amount of input data available for the real problem—the physical description of the environments at Hiroshima and Nagasaki; that includes everything from the source definition, to the humidity, to the housing configuration, to the direction people were facing. And that pretty much constrains the accuracy. Therefore we are here now to try to get feedback; that is, the radiation physics group is trying to get some feedback in the presence of funding-agency representatives to find out what both groups think is feasible and is reasonable in order to support the needs of the radiobiological group, which is going to be the recipient of the results.

Kerr: I would like to put things in perspective. Several years ago there were large unexplained discrepancies in the dosimetry, not only between the neutron transport calculations and the T65 dose estimates but also among the various sets of neutron transport calculations. We have made significant progress in resolving these discrepancies. I think the end is in sight; we know what the problems are and what needs to be done to obtain results we can have confidence in. We must compare the results with experimental data so far as possible and try to verify them. But the situation looks brighter than it did, even a year ago.

Bond: That is a helpful statement, but it would be much more helpful if you could follow it up with something more concrete. Some of the people in the radiation physics group know exactly what directions are being taken, but many others do not and are interested. Can you give us more detail on what the physics group is doing collectively and what parts are being done by whom?

Kerr: I think most of us agree that the top-priority project right now is the two-dimensional calculation of radiation leakage from the Hiroshima weapon. We desperately need that, and we can't do any more on finalizing the dose estimates until we have it. We will have to depend on those at Los Alamos and Livermore and possibly Oak Ridge—Joe Pace and Dave Bartine—to verify the uncertainties in the calculation. The theoretical calculations for the Hiroshima weapon will not resolve the question of yield; they will give a range of possible yields and the probabilities that the yield was a certain one within that range. Something else that needs to be done is simply to go back and collect the relevant data related to the yield and have them reviewed by a panel of knowledgeable people. We need to select the best available data and to base the yield on the recommendations of the panel. Finally, the air transport calculations of prompt and delayed radiation definitely should include some sensitivity studies; we need to establish the precision in the final calculated values. The calculations must take into account the effect of the cross-section data on the final results, the effect of uncertainties in moisture content, and other things that may have an impact on the final results. We need to compare these with all the neutron activation data, and we do have experimental data to compare them with. The final results will gain an added measure of confidence if we can duplicate reasonably well the activation data of the neutrons and can at least verify gamma exposures by thermoluminescence measurements on roof tiles and other samples. We should start preliminary studies on house-shielding factors and organ doses, although these should be given lower priority than the air transport calculations.

Groer: There are now Bayesian techniques available that permit expression of the uncertainties in the input parameters for the dose calculations (e.g., the yield of the weapons) with the aid of prior subjective-probability densities. The uncertainties in these parameters can then be propagated to yield densities for the calculated doses. These techniques involve elicitation of subjective probabilities through interviews of experts by skilled interviewers and are widely used in the business world and in other situations where decisions under uncertainty have to be made. Many papers have been written about these techniques and, although they have rarely been applied to problems in physics, in principle there's no reason why they couldn't be used in this context.

Eisenhauer: This is a special case of the question raised by Dr. Radford earlier, about how the uncertainties in the dosimetry should be expressed. Would some of the people doing calculations comment on this for the benefit of the biologists and medical people?

Loewe: I've struggled with this problem in working on dose uncertainty with the biologists at Livermore. Yesterday I indicated my feeling for the uncertainties in the free-field portion only. I like to think in terms of the probability that a given change in dose will have to be made in the future. I consider a future change of a factor of 2 in free-field dose to be sufficiently unlikely to be generally disregarded. A change of 40 or 50% is not so unlikely and may well happen. A change of only 20 or 30% is perhaps probable. I'd like to give a probability distribution for a range of uncertainties, and I'd like to see that range of uncertainties and the associated probabilities shrink as additional work is done. That is my approach, and I hope it's useful to the biologists because I don't know what else to do.

Jablon: The estimates of yield are often given with a ±1 or a ±2. I am not certain just what these mean, and I suspect the people who wrote them aren't either—maybe they are standard errors or probable errors. To answer Dr. Loewe, a statistician would replace the point estimate with a probability distribution. It used to be that a lot of data was needed to make a probability distribution, but then the Reverend Bayes was rediscovered and "prior distributions" were legitimized. You can put your uncertainty into some kind of explicit form in terms of a probability distribution having either a normal form or anything else that seems suitable. If you do that with all the measurements you make, then when you fold things together, you can also fold together these error-probability distributions and end up with a final dose estimate which itself has an error-probability distribution associated with it. I don't want to minimize the difficulties of doing that or the problems the statisticians would have to cope with, but there is a way of doing it, and it's a pity we are so far behind the state of the art in this respect.

W. H. Scott: My first point is that the uncertainty is a function of range. In discussing uncertainty it's important to specify the range because there's a big difference between one kilometer and two kilometers. It is easier to get more-accurate data closer in. The computational problems get more difficult at the further ranges; therefore our higher doses are perhaps more certain. We had 100% uncertainty in the delayed gammas at 2 km, which translated into maybe a 20% effect on the total dose. There are a great number of uncertainties, and it is not clear which are correlated and which are not. I am concerned whether, in putting normal distributions on each of them and doing an analysis of RBE's, we won't be misinterpreting some correlations that we, as calculators, know about in cases where you, as radiobiologists, are not aware that two errors might be anticorrelated. Some care and some interchange on all our parts will be needed in studying these kinds of effects. My second point is that there is uncertainty in the house-shielding factors themselves. We are recommending that we calculate a number of examples (we're not sure just how many) as well as possible to show all the effects of the spectral differences. We won't want to apply that technique to every one of the survivors in the data base. We will want to come up with a recommended way of treating the shielding factors which will include an uncertainty, although it is hard to see how that can be a very exact uncertainty—it will be our best guess. I think, as we heard at the Minneapolis meeting, that the biologists will have to learn to live with the uncertainty of physics. We are doing the best we can and hope to advance the state of the art, but we could go on forever trying to improve our knowledge of uncertainties. We don't think that is what is needed.

Song: I have found some very interesting statistics here. Of eleven speakers yesterday and today, three discussed projects funded by the DOE (Department of Energy) Office of Energy Research; four, funded by the DOE Weapons Program; and four, funded through the Defense Nuclear Agency. As a member of a funding agency, I would like to know whether this work is well coordinated so that those speakers know each other and know each other's studies and how they are related. Regarding the improvements or advancements, what is our target? Are we shooting for a 10% uncertainty limit or 15%? And how far into the future are we going to continue funding? Another point is that we are always subject to the threat that the RBE is going up by a factor of 3, or 5, or 10, and so on, and we have to be prepared for that. I have an uneasy feeling as to what's going to be the next step as far as RBE's are concerned.

Thiessen: Coordination of the funding was actually one of the reasons for this workshop. But DOE and DNA, which you mentioned, don't really think in those terms. The most important thing DOE is responsible for is the American input into the Radiation Effects Research Foundation (RERF) program. The dose-reassessment project is viewed as contributing to that program and is taken very seriously in that we at DOE will support whatever is necessary to bring it to an expeditious end. That is easier said than done, and that's why we wanted to get people together to tell us (DOE, DNA, and whoever else is willing to fund) what needs to be done. We are not asking for a price tag yet, but I have never had any problem getting people to state a funding requirement—the problem is to reduce it to reasonable dimensions, but that's a different problem. We give dose reassessment a high priority, and that means budget cuts will not seriously affect it. Also, we have a commitment to the Government of Japan that we cannot renege on.

Groer: If you approach the problem of uncertainty in the dose estimates as a Bayesian, you can answer questions about the cost of a certain amount of information within the framework of decision analysis. The classic introduction to this topic is Howard Raiffa's book *Decision Analysis* (1970).

Eisenhauer: There should be a recommendation to the people funding these efforts that some attention be given to suggested guidelines for the accuracy needed in each step in order to get the required degree—as yet unstated—of overall accuracy.

M. Mendelsohn: Before you do this exercise, which I think has to be done, I'd like to point out that there are several bases on which one should decide accuracy. We have been emphasizing the technical one, the physical aspects of accuracy; however, the biological aspects of accuracy are a separate set, and they need discussion as well. There are other aspects, including the problem of credibility. We must find a level of accuracy and of consensus which reestablishes the kind of credibility we had back in the T65D days. I don't mean that we should arrive at a dose and then lock it away in a vault—that was the mistake we made with T65D—but rather that we should reach a point where the involved scientists, administrators, regulators, and so forth, are satisfied and agree to "lock up" the dosimetry except for a continuing overview to identify new information which suggests that it has to be opened up again. I have found this meeting extremely reassuring as compared with some of the earlier happenings since this issue broke open; here I sense convergence rather than divergence. I think an acceptable dosimetry will be obtained, and, provided the right judgments are made about the sequence, it should be obtained very effectively. I strongly support the SAI (Science Applications, Inc.) suggestion to put the data base in a form that can be iterated so that the issue can be reopened without too much difficulty. Still another aspect, the most difficult to deal with, is the ethical one. The data we are working with are from an occurrence which we hope will never be repeated and which will be remembered for a long time; this brings in the criterion of value to posterity in judging how much should be invested. All these points should be kept in mind, and we should be careful to see that we are not holding back, that we are not being penny-wise and pound-foolish.

Kaul: When I was at the Defense Nuclear Agency in the early 1970's, I once showed my superiors that, in our research program, we had obtained 10% accuracy in a specific technical area, and I was criticized for this. How could I get 10% accuracy, they asked, when other technical problem areas that were of similar importance in terms of program utilization were not resolved to better than a factor of 2? I explained that it wasn't premeditated and it wasn't my fault that we had obtained 10% accuracy, although I hadn't discouraged it. I mention this to show that you don't go into these calculations with preset accuracy criteria. If ever there was a slow-motion exercise, it is research of this kind. The iteration takes six months to a year, after which you have to assess what parts of the problem have accuracy problems in relation to the other parts and to the planned application of the results. At the end of the first iteration, you realize that, if, at the end of the second iteration, some parts are out of balance, that is a problem to be considered then and not now. You cannot decide in advance to do everything to 10% accuracy, because that may not be feasible or even necessary.

Auxier: In relation to what Mort Mendelsohn said, I hope and I believe—as we leave this symposium—that we have a great deal of togetherness. It is appropriate for me to say that because I am about the only active member of the original team and consequently am the one who has to do the speaking for the dozen or so people involved over the years. I promised myself a year or two ago to try to keep quiet because, as the person who had to summarize all the work in the T65D, I was the logical person to speak for it and I wanted to do as little of that as possible, hoping and believing that science would be served better if the younger generation converged on it from different angles and that eventually we would come out with the right answer. Lest some of you interpret my role as the grain of sand in the oyster or as the devil's advocate in trying to make sure occasionally that the system stays honest or lest you feel that I am too involved in it to remember, let me quote from the Ichiban report (Auxier, 1977), the last page:

> Because of the uncertainties related to numerous assumptions, such as the equivalency of the neutron spectrum to HPRR and Little Boy, additional calculational studies are underway using cross sections that have become available within the last decade.

I wasn't talking about our calculations then. My next stage is a statement to Dr. Thiessen and others. We haven't asked how we got to where we are now. The reason the old team is gone (I don't know why I am the only survivor) is because the funding went away. When we got the preliminary T65D in 1965, after a year we willed ourselves to say, "If this is as good as we're going to get, maybe it's good enough." Even back when Dr. Charles Dunham was still director of the old AEC Division of Biology and Medicine and Bob Wood was there under the whip, he kept saying, "You physicists have been at this long enough. You should have the answers." We replied, "We keep discovering things every day that we didn't know, and the physics should be kept abreast of the medical studies in Japan." No one would believe how many times I have said that except the funding agencies and maybe some of those who make proposals. But the money dried up because we'd been working for a long time and we had an answer, though we knew at the time it was subject to uncertainties, and that's why I put that statement in the Ichiban report. Now I am philosophizing. Sooner or later, even with Dr. Thiessen's best intentions at the moment taken into account, the time will come when the pressures will be to stop; and I agree with Peter Groer that some analyses will have to be made when the techniques get good enough, but the scientific community will not necessarily think they are good enough when the time comes to stop. I strongly endorse the work that is going on. I will still challenge the new work right down to the end, but I do believe that eventually we will have the right answer. It may well be that the data Bill Loewe came out with first—even though it involved some numerical juggling—will provide the exact, right curves. We all have known for a long time that the spectrum was softer, but there were some reasons why we could not accept that initially as the chief and overriding criterion—the neutron activation products in Japan gave numbers that did not agree with that spectrum. George Kerr presented a beautiful scheme for tilting his bomb 15° and doing an experiment, but that's not adequate, it's not correct, and it can't be done. We must take a realistic look at all these data and set some reasonable lower limit for the neutron dose at the big distance. I'll try to ascertain that we do that properly, and I think, as George Kerr said, that within a year or two we will have resolved it, but, also as he said, we won't be able to resolve it unless we get the multidimensional hydrodynamic calculations out of Los Alamos. I've been waiting since 1956 for those and so I'm not holding my breath, yet, but I would like to see them very, very much.

Liverman: I have tried to keep quiet during the whole course of this discussion, and I have learned a great deal. I've spent many years supporting radiation standards utilizing the data that have been generated, but John Auxier is correct in saying that support for dosimetry almost disappeared at a critical point in time because of constrained budgets and other priorities. The interesting things to me at this conference have been the material presented by Dr. Loewe, which should have been known to me sooner but was not, and Mort Mendelsohn's information about the RBE's at the low levels. There is still a lot of hue and cry in the United

States among those who have been exposed to very low levels of radiation that they should be recompensed financially, and there is still major dependence on the results of the studies in Hiroshima and Nagasaki as a basis for judging where radiation standards should be set. It would be good to have lots of money to support all studies at all times, but I think this conference has made clear the need for the radiobiologists and the physicists to converge in a way that they have not been willing—or have not been encouraged—to do before. I hope that out of this conference will come a plan for the three major funding agencies (I look at Gil Beebe here and wonder why the National Cancer Institute isn't heavily supporting this effort also, since they have a deep interest in such matters) to arrange, over the course of the next four or five years, for most of the unanswered questions to be resolved in a very sharp, though perhaps not final, way, at least to the point where we thought we were 15 years ago when it was said, "We've done enough of this damn dosimetry, now let's get on with business." I hope a definite plan emerges, if not from this session then over the course of the next few weeks, as to how to proceed most effectively to spend whatever funds can be made available to sharpen the calculations and the dose estimates. I have a continuing interest in this area as do Vic Bond and Seymour Jablon. Seymour was on the U. S. team that I led in creating the binational foundation RERF, and I continue to serve on its board. I will be pushing to get more of Thiessen's and everybody else's money to continue to support that program. I think this meeting has been worthwhile, and I hope sessions like this continue because it is from such joint meetings between the radiation physicists and biologists that better understanding will come.

Sinclair: I don't think we need to go over what needs to be done, because in many ways this meeting has been a progress report rather than a planning session. I am pleased to see that some people are reporting on work initiated as a result of things we at NCRP (National Council on Radiation Protection) started some time ago. The NCRP Task Group on Atomic Bomb Survivor Dosimetry, set up in 1976, has taken a number of steps that have led to some of the results presented here, even though many of the workers were from other disciplines with different points of view. The task force obtained funding from DOE for various kinds of work and from DNA for certain kinds, and I am pleased to see some of those efforts bearing fruit. Besides the things we've already got going, I want to emphasize again that we must have as much experimental confirmation of these calculations as we can possibly get. I was pleased to hear that Bill Loewe has some ideas about new activation studies, and I imagine other people have some ideas, too. Whatever funding agency is involved should consider any such proposal very seriously because it is experimental confirmation that we need, since the calculational techniques seem already to be very good. Two important biological considerations relate to neutrons and gamma rays. The biology discussion here has tended to concentrate on neutron RBE's. Neutron toxicity is one of the most difficult protection problems because our knowledge is so limited. Any neutron-effectiveness study that involves human beings is tremendously important, and this particular one presents a lot of difficulties. It will be hard to decide to what extent the neutrons have contributed to the biological effects, especially at Hiroshima, now that their estimated number will probably be a good deal lower, though not zero. NCRP has taken the neutron problem very seriously for many years and is likely to take it even more seriously in the future. However, the question of gamma-ray risk estimation is the aspect which has been primarily publicized in the press and outside the scientific community because of the impression that changes in dosimetry might lead to substantial revisions in estimates of gamma-ray risk, and most occupational and public exposures are to gamma rays rather than to neutrons. More-recent appraisals of the meaning of the Livermore and the Kerr estimates of the gamma rays at Hiroshima indicate that they will not change the gamma-ray risk estimates by more than about a factor of 2. I hope that statement won't be wrong after all the details of shielding and other calculations, which obviously have to be done with some degree of thoroughness, are finally completed. We are dealing with *the* most important source of data for gamma-ray risk estimation, even though we have many other sources also and they tend to fall in the same range. However, the Hiroshima and Nagasaki data clearly are the most quantitative, at least until sometime in the future when we might have a large enough population of people irradiated at low doses to provide a reliable upper limit to our risk estimates. The NCRP has given a good deal of thought to this question already, and I anticipate they'll give a good deal more. I hope that, in considering our program in the future (the task group may start this tomorrow), we will also consider other task groups which might be necessary in this area and will make some proposals to the funding agencies about how the NCRP can help resolve this issue. One way to proceed might be to involve many of the participants in some of the planned work, but obviously this would have to start with proposals and suggestions and perhaps invitations to people in the field in order to put our best foot forward in solving the scientific problems.

Moghissi: At this meeting some of us who have worked in this field for some time have been encouraged by what appears to be an emerging consensus on this particular subject. As long as I was at the receiving end of the funding as a researcher, I felt that the bureaucrats in Washington never understood our needs and never gave us enough money. Now that I'm at the other end, I feel the researchers always want more and are never satisfied. But this is one area where saving money may be inappropriate. The significance of the work reported here goes far beyond the weapons program and/or the radiation effects program; it encompasses the entire field of carcinogenic-risk assessment and its impact on environmental protection. A great deal of carcinogenic-risk assessment conducted today is based on the carcinogenic-risk studies in the radiation field. As a biokineticist, I was disturbed by Dr. Rossi's implication of a synergism between gamma rays and neutrons at levels expected under environmental conditions, because of the mechanism involved. The models and the calculations presented by the three groups here would not accommodate synergism.

Bond: The synergism you refer to was first shown by Frank Ngo some time ago and is not unexpected. The explanation is that radiations of any linear energy transfer (LET) produce some "subeffective" cell damage that cannot alone cause an all-or-none effect to occur. With multiple hits on a cell, however—and if the dose and the dose rate are high—two or more subeffective hits can combine to produce an all-or-none effect. With low-LET radiations such subeffective hits combine autosynergistically as the dose is increased, to yield the familiar βD^2 portion of the overall dose–response curve for single cell effects. With high-LET radiation, however, the contribution of the βD^2 term is very small (i.e., the dose–response curve is essentially linear). Thus synergism can be demonstrated normally only at quite high doses and dose rates. Thus, in my opinion, synergism between neutron and gamma-ray effects is unlikely to play a large role. In any event it will not explain the uncertainties and discrepancies among various dose–response curves which have been discussed here.

Groer: Regarding the analysis of the leukemia mortality data, I would like to present some results of joint work with Drs. T. Ishimaru and A. Brodsky and Ms. Yasunaga at the Radiation Effects Research Foundation and Dr. M. Ichimaru at the University of Nagasaki. A more comprehensive description of this analysis was presented at the recent Radiation Research Society meeting in Minneapolis. We found that the estimated cumulative distribution functions (CDF's) for the time from the start of follow-up (Oct. 1, 1950) to death from leukemia for the following T65R dose groups are not significantly different: for N (0, 1 to 9, 10 to 49, 50 to 99) and for H (0, 1 to 9, 10 to 29). N and H denote the two cities, and each group of numerals indicates the range of T65R tissue kerma in air. This result means that for these groups a difference in radiation effects between the two cities cannot be established. This finding is consistent with the "new" dosimetry but casts doubt on the validity of "extrapolated" RBE values for low doses. The situation for the high-dose groups is not as clear-cut. The CDF's for H300 to 399, H400+, and N400+ are not significantly different. The same is true for H200 to 299 and N200 to 299. But the groups N50 to 99, N100 to 199, and N300 to 399 differ from the corresponding Hiroshima groups.

Ellett: Regarding Mike Bender's paper, I'm not sure that, a priori, from the data on microcephaly at Hiroshima and Nagasaki, one could say that the two cities are different. We took these data to some statisticians—not biostatisticians—at MIT (Massachusetts Institute of Technology) and asked them for an analysis of the response in the two cities. Not knowing anything about Hiroshima, Nagasaki, or neutrons, they sent back a report that was very surprising to us: "There is no difference between these two data sets." When the data are examined without knowledge of the neutron dose, this is true. There was no more microcephaly in one city than the other. Compared with Hiroshima, there was less at low doses at Nagasaki but more at high doses. When asked whether their test showed a difference between the two cities greater than that expected on the basis of sampling error, these statisticians answered no. If you do not use the break at 18 months, as did NIH (National Institutes of Health), but study all the periods after exposure, you can find some period where you might see, statistically, a borderline significant difference between the two cities, but you have to pick the right breakpoint. As usual, the Nagasaki sample is very small; almost all the data are from Hiroshima. But I wish Mike Bender would take a fresh look at those data to see whether they really support the case for a difference between the two cities. The original literature shows that the people doing the investigation in the beginning ascribed the difference between cities not to their statistics but to their prior knowledge of the neutron dose, which has since become questionable. The same may be true also of other bioeffects ascribed to neutrons.

Borg: This is a comment on dosimetry, for the record. Some years ago when Charlie Eisenhauer and I were members of a predecessor of the Defense Nuclear Agency, the Armed Forces Special Weapons Project (AFSWP), we used transport equations that were solved on the old SEAC computer at NBS (National Bureau of Standards) to carry forward calculations for gamma dosimetry both for weapons and for devices tested in Nevada through the mid-1950's. These calculations, which were based on what these days are called secondary gammas from neutron captures in the air and on fission source gammas, were compared with the film-badge measurements made at the various tests. This involved hard work in bringing together, in an empirical way, source terms, so to speak, for gammas for those various devices and weapons. This work was recorded in a document which is still classified, AFSWP Report 502(B), and in an unclassified document, AFSWP Report 502(A) entitled, "Spectral Distribution of Gamma Rays Propagated in Air," which is available from DNA and the

Library of Congress. It was a long-ago predecessor to much of what is being done now, and, though not nearly so elegant, may contain some useful data to check calculations against.

Charles: Warren Sinclair is of the opinion that the new dosimetry is unlikely to change the low-LET risk estimate by more than a factor of 2. I strongly support that. If we ignore the bomb data but consider the other relevant data given in the BEIR III (1980) or UNSCEAR (1977) reports, then we can derive low-LET risk estimates that are probably higher than the present ICRP (International Commission on Radiological Protection) estimates, but by no more than about a factor of 2. Thus there seems to be no undue pressure to change the low-LET radiation standard. Obviously we have little information on which to base high-LET quality factors for late effects in humans. It may be fruitful to admit this in order to encourage follow-up studies by the increasing number of radiotherapists around the world who are using neutron therapy. Clinical data already exist in the United Kingdom which would not support increases in neutron quality factors for the production of cataracts which impair vision (Charles and Lindop, 1979).

Bond: In closing this meeting I would like to say I was very pleased at the free exchange of ideas here. It was also particularly pleasing to hear several individuals comment on the amount of progress which has taken place over the past couple of years and which is continuing. That is, things do seem to be converging; the individuals involved do seem to know where they are going; and, even though it cannot be spelled out in detail when, it is apparent that agreement on answers should be reached in the next few years. I wish to thank all the participants, speakers and discussants alike, for the free exchange of information. Your participation is appreciated.

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Subject Index*

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ENERGY DESKBOOK

Samuel Glasstone

The sheer magnitude and complexity of the national energy effort make it a difficult task for anyone seeking to understand the scientific and technical development involved. It was the needs of the layman and busy specialists, such as scientists, engineers, and administrators, that prompted the Department of Energy to contract with Dr. Glasstone to prepare this deskbook.

Energy Deskbook contains information on the background and status of energy development. Energy-related terms are defined, and current and potential energy sources and their use are described. Energy sources covered are biomass, coal, geothermal, hydropower, municipal waste, natural gas, nuclear, oil shale, petroleum, solar, tidal, and wind. Combining the features of a dictionary and an encyclopedia, Dr. Glasstone has emphasized general principles rather than technical details. Cross references, which are used freely to minimize duplication, are indicated in the text by words or expressions in boldface type.

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RADIOACTIVE DECAY DATA TABLES

A Handbook for Application to Radiation Dosimetry and Radiological Assessments

David C. Kocher
Oak Ridge National Laboratory
Oak Ridge, Tennessee

The estimation of radiation dose to man from either external or internal exposure to radionuclides requires a knowledge of the energies and intensities of the atomic and nuclear radiations emitted during the radioactive decay process. The availability of evaluated decay data for the large number of radionuclides of interest is thus of fundamental importance for radiation dosimetry.

Decay data are listed for approximately 500 radionuclides, which include those occurring naturally in the environment, those of potential importance in routine or accidental releases from the nuclear fuel cycle, those of current interest in nuclear medicine and fusion reactor technology, and some of those of interest to Committee 2 of the International Commission on Radiological Protection for the estimation of annual limits on intake via inhalation and ingestion for occupationally exposed individuals. This handbook supersedes Report ORNL/NUREG/TM-102, which was concerned only with radionuclides from the nuclear fuel cycle.

CONTENTS: Introduction; Review of Radioactive Decay Processes; Preparation of Radioactive Decay Data Sets; Computer Code MEDLIST and Description of Tables of Radioactive Decay Data; Applications of Decay Data to Radiation Dosimetry and Radiological Assessments; Parent-Daughter Activity Ratios; Accuracy of the Data and Uncertain Decay Schemes; Appendix 1: Symbols and Definitions; Appendix 2: Index to Tables of Radioactive Decay Data Sets; Appendix 3: References for Radioactive Decay Data Sets; Appendix 4: Diagrams of Radioactive Decay Chains; Appendix 5: Tables of Radioactive Decay Data.

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