EXECUTIVE SUMMARY

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A new assessment of the dosimetry system used by the Radiation Effects Research Foundation (RERF) for estimation of radiation doses to the atomic-bomb survivors of Hiroshima and Nagasaki has been completed. This reassessment has defined the parameters for a new dosimetry system (DS02) that replaces the existing dosimetry system (DS86). An independent group of scientists, the Joint U.S.-Japan Working Group, was responsible for the formulation of DS02.

Beginning in the autumn of 2000, the Joint Working Group undertook a comprehensive evaluation of the calculations that comprise the RERF dosimetry system and the measurements that are used to verify those calculations. This reassessment was mandated and supported by the U.S. Department of Energy and the Japanese Ministry of Health, Labour, and Welfare in an effort to resolve the apparent discrepancy between measured activation levels in materials exposed to neutrons at the time of the bombing and levels of neutron activation calculated by DS86.

During the course of this dosimetry reassessment, the Working Group, comprised of scientists from the U.S., Japan, and Germany, have redone all aspects of the Hiroshima and Nagasaki radiation transport calculations, made new fast-neutron and low-background thermal-neutron measurements, upgraded the calculation of the radiation shielding provided by terrain and large buildings, conducted a comprehensive reassessment of all *in situ* radiation measurements and performed an uncertainty analysis of the dosimetry system.

The new radiation transport calculations produced during this reassessment agree with both gamma and neutron measurements out to distances from the detonations at which these *in situ* radiation measurements become indistinguishable from background, effectively resolving the neutron discrepancy. At distances from the detonation where activation measurements could not be reliably distinguished from background, measurements were found to be too uncertain to be used for the evaluation of calculations.

The parameters and calculations that provide this agreement with measured *in situ* radiations that clearly arises from the bombs comprise the basis for the new DS02 Dosimetry System. While the changes that comprise DS02 resolve the neutron discrepancy, the values of the free-field radiation kerma differ by no more than 10% between DS86 and DS02.

Events Leading Up to the Current Dosimetry Reassessment

The current Joint U.S.-Japan Working Group on the Reassessment of A-bomb Dosimetry was formed after more than a decade of work to resolve what has come to be known as the "Hiroshima neutron discrepancy." This apparent discrepancy was characterized by measurement of higher levels of thermal neutron activation than were calculated by DS86, particularly at distances of more than a kilometer from the hypocenter of the detonation, where most survivors are located. DS86 also calculated more thermal neutron activation directly under the bomb than were measured. In short, the variation with distance or slope of the calculated thermal neutron activation in Hiroshima did not match that of the measured thermal neutron activation. This problem has been the subject of debate in radiation dose reconstruction circles, the topic of numerous scientific papers, a source of uncertainty to Japanese atomic-bomb survivors, the basis of lawsuits over compensation rights, the subject of a U.S. National Academy of Sciences (NAS) evaluation, and a persistent uncertainty for the radiation risk assessment community, which bases most of its analyses of radiogenic disease on the follow-up studies of the Japanese survivors conducted by the RERF.

DS86 was developed as a sequential set of modular radiation output, transport, and shielding calculations linking the calculated radiation from the bombs to the survivor dose for each of fifteen organs from both gamma and neutron radiation exposure. The modular structure of DS86 permits testing of dose calculations and modification of components within the system as additions, changes, or needed refinements are identified. During the development of DS86, the gamma component of the radiation was verified by comparison with measurements of the thermoluminescence (TLD) created within ceramic materials by gamma rays from radiations generated by the bombs. Given that over 95% of the radiation dose to survivors is from gamma rays, DS86 was adopted despite the fact that the neutron calculations could not be verified with the relatively small number of neutron activation measurements available in 1986. Despite confidence in the gamma dose calculated by DS86, the final report on that dosimetry system said the thermal neutron fluence as represented by the cobalt activation measurements "contradicts the calculated values by an ever-increasing factor that is five at 1,000 m". A review of RERF dosimetry, completed just prior to this reassessment by the U.S. National Academy of Sciences Committee on RERF Dosimetry, confirmed the persistence of this discrepancy despite the efforts to resolve it since 1986.

Efforts to address this neutron discrepancy began almost immediately after the installation of DS86 at RERF. The first efforts were to make additional neutron activation measurements. Then there was new work on the calculations. Finally, during the current reassessment, there was the reevaluation and reconciliation of the two. The efforts to address this problem resulted in roughly 300 measurements of both thermal and fast neutron activation samples since 1986. Japanese scientists made over 200 measurements of europium-152 (^{152}Eu) alone. German, American, and Japanese scientists used accelerator mass spectrometry (AMS) to measure chlorine-36 (^{36}Cl) from concrete and granite samples. U.S. and German scientists developed the chemical separation and AMS measurement techniques for nickel-63 (^{63}Ni) from copper samples, and then made ^{63}Ni measurements from copper samples. These measurements, added to the 17 sulfur activation (^{32}P) measurements made immediately after the bombing, the roughly 100 cobalt (^{60}Co) measurements made over the years, and approximately 140 measurements of gamma-ray induced thermoluminescence, largely from roof tiles used as TLDs, have now produced slightly

over 650 radiation measurements with which calculations can be compared. This large number of measurements, not available when DS86 was being developed, provides the basis for understanding and resolving the dosimetry discrepancy.

At the time the DS86 report was issued, the apparent discrepancy between the measured and calculated activation was widely assumed to be a defect in the calculations. Beginning in 1987, efforts to "fix" the calculations began. These efforts were all directed toward bringing the calculation into line with the neutron activation measurements, which, in Hiroshima, indicated approximately three to five times the calculated activation. These efforts were concentrated in three areas: improvement of the discrete ordinates techniques for radiation transport to obtain better agreement with Monte Carlo calculations; achieving better resolution of the oxygen, nitrogen, iron and uranium cross sections; and evaluating alternative output and detonation hypotheses for the Hiroshima bomb. This work is summarized in the 2001 NAS report on DS86 and in this report.

Refinements since DS86 in discrete ordinates techniques and better resolution of the cross sections have improved radiation transport calculations in general, and thermal calculations in particular. While significantly improved discrete ordinates transport calculations resolved any disagreement between measurements and calculations under the Nagasaki bomb, they did not change the calculations sufficiently to match the Hiroshima measurements beyond one kilometer from the bomb. This finding prompted the serious exploration and evaluation of alternative output hypotheses for the Hiroshima bomb. Efforts were made to "create" an output spectrum for the bomb that would match the distant thermal neutron measurements, either by adding fission-spectrum neutrons to the existing Hiroshima leakage spectrum, arbitrarily boosting the leakage spectrum near the "oxygen window" (cross section minimum at 2.3 MeV), or hypothesizing a crack in the bomb case that would permit some neutrons to escape the bomb case uncollided. All of these trials were found either physically impossible to accomplish or incapable of matching all of the TLD, fast- and thermal-neutron measurements. The failure of any of the improvements or "unconventional" outputs to suggest a way for known radiation transport physics to match all of the Hiroshima measurements led to efforts both to identify a method to check the few existing fast-neutron measurements and to reevaluate all *in situ* measurements.

Convergence of several events during 2000 led to the formation of the Joint Working Group. More than a decade of measurements, calculations, and analysis had begun to focus on areas of possible solution. New nuclear computer models and tremendous increases in computing power now made it possible to conduct a 3-D Monte Carlo calculation of the output from the Hiroshima and Nagasaki bombs, which the NAS Dosimetry Committee had recommended. These developments and concern in the U.S. about the impact of a neutron discrepancy in the RERF dosimetry on future radiation risk standards, led the U.S. Congress to provide a one-time appropriation in fiscal year 2000 to resolve the neutron discrepancy. While this Congressional mandate did not provide the full funding required for this task, it did provide the impetus for U.S. action. During October and November of 2000 the U.S. Working Group was formed and in December 2000 merged with the ongoing efforts in Japan to reassess the RERF dosimetry. While this effort was designated as the U.S.-Japan Working Group on the Reassessment of A-bomb Dosimetry, there has always been a strong collaboration with the scientists from the Technical University of Munich in Germany. Their collaboration and contributions have been invaluable, and the use of their tandem accelerator has made the Accelerator Mass Spectrometry (AMS) measurement for fast neutrons in copper samples possible.

The Current Reassessment

The attempt to resolve the neutron discrepancy was assigned to a working group because, at the outset of the reassessment, there were a number of recommendations, including those of the NAS Dosimetry Committee, but no definitive approach to the problem. While it was easy to agree that any reassessment of the dosimetry system should include improvements in terrain and large structure shielding calculations and the reconciliation of current and World War II maps, there was no consensus on how or whether the Hiroshima neutron discrepancy could be resolved. There were those who thought the solution to the neutron discrepancy must be in the recalculation of the output of the bombs, and those who thought that it lay in corrections to measurements. Until the efforts of the Joint Working Group settled these basic questions, it was not apparent that a solution could be obtained, or whether the solution would entail refinements to the existing dosimetry system or changes in basic parameters of the calculations.

The initial emphasis of this reassessment focused on the recalculation of the radiations from the bombs, but shifted to the measurements as the importance of unaccounted-for background in the measurements was fully appreciated. By working through the alternatives, the Joint Working Group developed and achieved the following major objectives for this reassessment of the atomic-bomb dosimetry:

- Complete re-calculation of the radiation output and radiation transport for the Hiroshima and Nagasaki bombs
- Reassessment of all existing *in situ* radiation measurements
- Completion of ^{63}Ni fast neutron measurements and their modeling
- Re-measurement of ^{152}Eu samples in an ultra-low-background counting facility
- Conduct of a quality control intercomparison study of thermal neutron measurements using ^{36}Cl from granite *in situ* samples
- Reconciliation of hypocenter locations on current city maps to those of the 1945 U.S. Army maps using known fixed anchor points
- Correction of *in situ* sample locations for identifiable errors and hypocenter adjustments
- Inclusion of shadow shielding from major terrain features into radiation transport calculation
- Upgrading of shielding calculations and models, especially for all large wooden structures such as schools, and the reconstruction of the shielding for large Nagasaki factories
- Conduct of a goodness-of-fit analysis for yield and burst height using *in situ* measurement data
- Determination of the parameters for a new dosimetry system that provides agreement for both gamma-ray and neutron doses
- Performance of an uncertainty analysis for the survivor dose calculations

The work done prior to the beginning of this reassessment provided both the significant insights into the discrepancy and the tools that made the resolution of the neutron discrepancy possible. Obviously, the problem was framed by the many *in situ* measurements since DS86 came into use. The development of AMS measurement protocols created not only a new source of thermal-neutron measurement, but also permitted the first check of the fast neutron measurements since 1945. The many ^{152}Eu measurements established a slope for measurements within the first 900-m slant range from the bomb. The refinements in the discrete ordinates techniques removed a major uncertainty that had existed because of the lack of agreement

between discrete ordinates and Monte Carlo calculations.

Perhaps the most significant and far-reaching improvements that occurred between DS86 and DS02 were the upgrades that were made in the Evaluated Nuclear Data Files (ENDF), which were upgraded from ENDF/B5 to ENDF/B6.2. This upgrade improved the angular distribution of the inelastic scattering of neutrons in iron, the number of neutrons released per fission of uranium-235, and the resonance and window structure of both oxygen and nitrogen. These cross-section changes directly and specifically improved the overall accuracy of the output source term calculation of the bombs, as well as the air transport of the radiations escaping from the bombs. Equally important is the increase in the number of groups into which the cross sections are now resolved for use in discrete ordinates radiation transport (DORT) calculations. When DS86 calculations were made using ENDF/B5 in the DABL69 broad energy-group structure, the cross-section data were contained in 46 neutron groups and 23 gamma-ray groups of discrete energy domains. However, the cross-section data for gamma rays with energies between 14 MeV and 20 MeV were not used in the DS86 calculations, and the DS86 results were presented in terms of 46 neutron groups and only 22 gamma-ray groups. Current computer capability has made it practical to use the very fine energy group structure in the VITAMIN-B6 cross-section library for DORT air-over-ground calculations. The VITAMIN-B6 cross-section library contains 42 gamma-ray groups and 199 neutron groups, 36 of which are now thermal energy groups with upscatter. This provides a significant improvement in the ability to calculate the transport of radiations to *in situ* samples, almost all of which are thermal neutron measurements, most of them near the ground.

The first priority of the current reassessment was to exploit the significant advances in both computing capacity and cross sections to perform the first three-dimensional Monte Carlo calculation of the radiation output spectrum of the Hiroshima and Nagasaki bombs modeling the entire geometry of the bombs. Thus, the first assessment point for the Joint Working Group was to see if the output from these calculations would provide a solution for the discrepancy. The new output calculation produced the same estimate of the Nagasaki yield as was obtained for DS86, but produced a nominal yield that is one kiloton higher than the previous yield estimate for Hiroshima. While these output calculations are different in detail from the two-dimensional calculations done twenty years ago, they produce no source of neutrons that would account for the discrepancy.

Confirmation that the neutron discrepancy was not due to the source-term calculations led to the systematic evaluation of other factors that could cause the discrepancy, including the radiation measurements that have been used to check the calculations. The evaluation of measurements was comprised of a successive series of steps and assessment points that began with the establishment of a RERF measurement database and efforts to accurately define the location, shielding, transmission factors and uncertainty for each measurement. A series of new measurements was made to evaluate possible measurement contributions to the discrepancy with calculations. The ^{63}Ni in copper samples was evaluated to provide a check of the fast neutron measurements made in 1945. These ^{63}Ni measurements were carefully compared to ^{63}Ni measurements made in unirradiated copper. The location of each copper sample was fully modeled, including efforts to account for activation due to cosmic rays. As part of a series of quality control and intercomparison studies, previously measured samples containing ^{152}Eu were re-measured in an ultra-low-background facility to determine at what distance from the bomb measurement could reliably be differentiated from the ambient radiation present in the sample and measurement facilities. Simultaneously, an intercomparison study of AMS ^{36}Cl

measurements was carried out among investigators in Japan, the U.S. and Germany to control for process bias in these measurements. New ^{36}Cl measurements were made in granite to control for the meteoric leaching of surface chlorine contamination into more porous concrete samples. Existing measurements of ^{60}Co, ^{32}P and TLDs were reevaluated to eliminate location errors, to adjust sample locations for hypocenter adjustments, to consistently account for transmission factors and measurement uncertainties, and to recalculate the measurements using the latest cross sections. This series of evaluations led to the joint consensus that neutron measurements made from sites beyond 1,300-m ground range from the hypocenter were too uncertain to be used for the evaluation of calculations.

Concomitant with this evaluation of the measurements, all of the air transport calculations were recomputed with ENDF/B6.2 fine-group cross sections and the 2001 LANL output spectrum. Benchmark calculations between discrete ordinates and Monte Carlo transport calculations were run. New delayed gamma calculations were run for both cities using ENDF isotope-specific spectra rather than the late-time measured sources used in DS86. The delayed neutrons were similarly updated in 1993. Transmission factors for *in situ* samples and the kerma factors for free-in-air to tissue conversion were upgraded. Detailed analysis of the effects of local environments on thermal neutron production was made to evaluate the effects of water in sample materials and elements that act as neutron absorbers and poisons. The yield, burst height, and hypocenter location were all evaluated and refined where necessary. The results of fast-neutron measurements in ^{63}Ni, low-background thermal-neutron measurements of ^{152}Eu, a quality-control measurement intercomparison for ^{36}Cl, and the reassessment of the existing ^{60}Co, ^{32}P and TLD measurements, all conducted as part of this reassessment, have demonstrated that the Hiroshima neutron discrepancy at survivor distances from the bomb (greater than 1 km) was due to unaccounted-for background in the measurements, not fundamental problems with the calculations. The over-calculation of neutrons directly under the Hiroshima bomb was due to a slight under-estimation of the burst height of the detonation. Correction of these two problems produces good agreement between the measured and calculated values at all distances from the bomb, effectively resolving the Hiroshima neutron discrepancy.

Bomb Parameters

Quantification of the parameters that describe the nuclear detonations is a first essential step in radiation dose reconstruction. Determination of the neutron and gamma-ray doses in Hiroshima and Nagasaki begins by defining the yield, or number of fissions occurring in the bomb. This then numerically defines the strength of the neutrons and gamma rays generated by the bomb. The accuracy of the calculations that ultimately define dose from this series of calculations is dependent on the accuracy of the parameters that define the detonation. Dose or the neutron activation in a sample used to verify the calculation is dependent on accurately knowing the distance from the epicenter of the detonation to the point of interest. For a device with asymmetrical geometry, like the Hiroshima bomb, it is also important to know the heading of the bomber and the tilt of the bomb at the moment of detonation. The tilt of the bomb is derived from drop tests of identical non-nuclear bombs. The epicenter is the point in the air where the explosion occurred. The epicenter is defined by the height of the burst (HOB) and the hypocenter (or point on the ground directly beneath the explosion). The current reassessment has confirmed the parameters used in DS86 for Nagasaki, while refining the yield, burst height, and

hypocenter for Hiroshima (Chapter 1).

The bombs that exploded over Hiroshima and Nagasaki were very different in design and composition. The Hiroshima bomb had a cylindrical geometry, housed in a massive steel casing, in which two subcritical components of highly enriched uranium were assembled into a supercritical geometry by propelling one toward the other. This is the only weapon of this design ever detonated. As such, verification of the parameters of the Hiroshima detonation is dependent on the calculation of the detonation and measurements of effects of the detonation made in Hiroshima. The Nagasaki bomb had a spherical geometry in which a subcritical ball of plutonium was compressed to supercriticality by a converging shock wave driven by high explosives. Other bombs of this design have been detonated in nuclear tests. These other detonations provide almost all the data used to verify the parameters of the Nagasaki detonation.

The basic parameters for the Nagasaki bomb have been and continue to be established and verified in fundamentally different ways than are the parameters for the Hiroshima bomb. The bomb detonated over Nagasaki was very much like other nuclear weapons produced and tested since World War II. This was the same type of bomb tested in the first nuclear detonation at Alamogordo, New Mexico in 1945 and after the war during nuclear tests Able and Baker at Bikini Atoll in 1946. The radiochemistry analysis of nuclear debris and fireball formation measurements from these nuclear tests was used to derive the yield of the Nagasaki bomb. All of the test measurements and an independent assessment of yield based on shock wave damage produce a Nagasaki yield of 21 ± 1 kt. The nominal yield of 21.4 kt, derived from the source term calculations carried out for the current reassessment, is in close agreement with these previous estimates.

During this reassessment, previous estimates of the hypocenter location, burst height and yield were evaluated. The advent of Geographical Information System (GIS) technology made it possible to reconcile the location of the hypocenter between the new, more detailed Japanese maps of Nagasaki and the World War II U.S. Army maps that historically have been used. Georeferenced landmark control points on maps and aerial photographs established the Nagasaki hypocenter on the new city map to be just two meters west of the location used for DS86. A sufficiently large and accurately characterized set of radiation measurements made it possible to use these measurements analytically to check the existing estimates of either yield or HOB. Using a well-established 21 kt for the yield and the refined hypocenter location in the analysis of the *in situ* radiation measurements using an analytic solver predicted a HOB within a few meters of the 503 m HOB used in DS86, despite the considerable scatter in the radiation measurement data. The analyses done during this reassessment confirm a yield of 21 kt at a burst height of 503 m as the best parameters to use in the calculations related to the Nagasaki detonation.

Overall, the confidence in the parameters for the Nagasaki detonation output is much greater than for Hiroshima because the Nagasaki device has been tested, measured and calculated repeatedly, whereas the Hiroshima bomb is the only one of that design ever detonated. While the yield can be calculated using the same calculation methodology as Nagasaki, the parameters of the Hiroshima detonation must be verified using measurements made in Hiroshima. Heretofore, the epicenter for the detonation was determined from evaluation of blast and thermal damage. The yield was estimated based on the theoretical calculation, blast and thermal effects, and the yield implied by the sulfur activation and TLD measurements. These “absolute” and “relative” indicators were combined to obtain the Hiroshima yield for DS86. The weighted average of these indicators of yield, which ranged from 12 to 18 kt, produced a 15.25 kt estimate of the Hiroshima

yield. Rounded to the nearest kiloton, DS86 used 15 kt as the Hiroshima yield.

Since DS86 was established, a number of the indices used to establish the Hiroshima yield at 15 kt have been reevaluated, and a significant amount of new radiation measurement data has become available. All of the newly acquired and reevaluated data clearly support a Hiroshima yield greater than 15 kt. The theoretical calculation of the yield for DS86 was 15 kt. The three-dimensional Monte Carlo output calculation done by the Los Alamos National Laboratory (LANL) for this reassessment produced a nominal yield of 16.1 kt. Within the theoretically possible range of Hiroshima yields, no yield of less than 15 kt or more than 18 kt was actually calculated by LANL, placing 15 kt at the low end of the range of probable yields from the theoretical calculations. A re-evaluation of the LANL critical separation experiment using the new cross sections indicates a yield of 16 kt for the Hiroshima device, not the 15 kt obtained 20 years ago using ENDF/B5 cross sections. Application of these new data to the same analysis used to establish the DS86 yield now produces a 16-kt estimate for the yield of the Hiroshima bomb. This analysis was taken by the working groups as support of the yield of 16 kt (±2 kt) calculated by LANL.

In addition to these traditional methods for estimating the Hiroshima yield, the accumulation of hundreds of *in situ* measurements provides a sufficient data set so the overall goodness-of-fit between measurements and calculation could be used to evaluate estimates of yield and HOB. Using an analytic interpolation tool developed specifically for these comparisons, it was confirmed that a 16-kt yield at a 600-m HOB maximized the agreement between the Hiroshima calculations and the radiation measurements while minimizing the variance in the agreement. This provided an overall quantitative assessment of the empirical impression that a 600-m HOB provided a calculated slope that better fit the data than the 580-m burst height used in DS86. For Nagasaki, the same type of analysis found the best agreement between measurements and calculations using the well-established 21-kt yield with burst height within a few meters of the previously evaluated 503-m HOB.

Significant improvements in the accuracy of the basic nuclear data contained in the cross sections have directly improved the calculation of the output and transport of the radiations from the bombs, especially Hiroshima. Changes in the nuclear data for iron, oxygen, nitrogen, and uranium from the ENDF/B5 cross sections used for DS86 to the ENDF/B6.2 cross sections used for the DS02 calculations have substantially refined the Hiroshima calculations and brought all the measures into much better agreement. The angular distribution of inelastically-scattered neutrons in iron was changed in ENDF/B6 to be forward-peaked, resulting in the greater penetration of 3 and 10 MeV through the thick steel case of the Hiroshima bomb. The number of neutrons released per fission in the uranium-235 (^{235}U) cross section is better defined, making for a more accurate calculation of the uranium bomb detonated over Hiroshima. These changes specifically improved the Hiroshima source term calculation.

Air transport of the radiation escaping from the bomb has also been improved through refinements in the resonance and window structure of total cross sections for oxygen and nitrogen. Given that the capture of neutrons by nitrogen in air is a significant source of prompt gamma rays, these changes have refined both the calculated neutron leakage through the high explosives in the Nagasaki bomb and the accuracy of the air-over-ground transport calculations. These changes, coupled with a new cross-section group structure carefully selected to better represent the structure of the dominant iron and oxygen cross sections, have provided significantly better nuclear data for the current calculations than were available when the DS86 calculations were performed.

Radiation Transport Calculations

The radiation dose for atomic-bomb survivors is the end product of a series of complex and physically sophisticated calculations, beginning with prompt neutrons and gamma rays generated in the fissile material of the bomb and ending in a neutron and gamma dose estimate for each individual survivor. Prompt neutrons are produced while the weapon is still intact and able to sustain the fission process. Delayed neutrons originate from fission products produced during the fission process. Gamma rays stem from several sources including the weapon itself prior to disassembly, the reactions of neutrons that escape the bomb as they interact with the air and ground, and from fission products after the bomb disassembles. Each of these radiations is accounted for by a separate calculation.

The first step in this dose reconstruction process is the calculation of the "source term" for the bombs. These calculations, which were done at the Los Alamos National Laboratory (LANL), simulate the explosion of the bombs and track the radiation intensities from production in the interior of the bomb to leakage (escape) at its boundary. These calculations also provide a simple description of the isotopic composition of the fissile debris, from which delayed radiation can be inferred. The radiations escaping from the bombs contribute, in most cases indirectly, to radiation doses to people at ground level.

Additional radiation transport calculations are required to evolve these initial distributions from the epicenter of the explosion through the air to the ground. These additional calculations are often referred to as the "transport" or "air-over-ground" free-field calculations. The first part of the air-over-ground calculation characterizes the fate of the radiations that escape directly from the bomb. These direct or "prompt" radiation transport calculations are carried out at the Oak Ridge National Laboratory (ORNL) using the output of the LANL source term. During this process the radiation can be absorbed and, possibly, re-emitted with a different direction, energy or particle composition. These "secondary" radiations are also transported to the point of interest as part of this calculation. The characterization of the "delayed" radiations is accomplished in a third calculation added to the results of the previous two.

The delayed radiation, which derives from the fission fragments in the bomb fireball, is a calculation carried out at Science Applications International Corporation (SAIC). The summation of this chain of transport calculations defines a free-in-air kerma estimate for survivors. Dose to an individual organ within a survivor's body is determined through further calculations that account for the shielding provided by terrain, structures and the body itself. During the current reassessment every aspect of these calculations has been redone and refined, beginning with the generation of radiation within the bomb through and including the fluence conversion factors that provide the coupling of the free-field fluence to the body. The radiation dose from the bombs is delivered within the first few seconds after the detonation. However, the calculation of the short-term processes is quite complex, requiring months of preparation and many hours of computation on a massively parallel computer.

Bomb Output Calculations

Defining the output of the bomb is the first and most defining step in the calculations of radiation dose from an atomic bomb (Chapter 2). This is why the output from the bomb is often referred to as the source term. It defines the number and spectral energy distribution of the

neutron and gamma rays from the bomb. The current LANL calculation source term is the most refined and complete calculation of the Hiroshima and Nagasaki output accomplished, thanks in large measure to massively-parallel computing capacity that is roughly 10^4-10^5 times that available nearly 20 years ago when the DS86 calculations were completed. The completeness of this, or any calculation as large and complex as the source term for a nuclear detonation, is limited by computer capacity. The calculation of these bombs for DS86 was limited to a two-dimensional representation of a subset of the essential components of the bomb. The output of that calculation contained 38 neutron groups and 27 gamma-ray groups, each of which contained 20 directional bins. Since DS86, cross-section libraries have had three generations more of refinement, significantly improving the transmission of neutrons through such basic materials as oxygen and nitrogen in air and high explosives and in the iron that constitutes the case of the Hiroshima bomb. Together these developments have made a significantly more detailed and complete calculation of the source terms for the bombs possible. The current LANL source term was a three-dimensional coupled hydrodynamics and Monte Carlo radiation transport calculation of the entire geometry of the detonation. The calculation used the ENDF/B6.2 cross-section library to produce an output containing 200 neutron groups, 43 gamma-ray groups, each of which is divided into 40 directional bins. One additional neutron group (0 to 1×10^{-11} MeV) and one additional gamma-ray group (0 to 1×10^{-3} MeV) were added the the VITAMIN-E data set for use in the MCNP leakage calculations for the Hiroshima and Nagasaki bombs. As expected the neutron and gamma-ray leakage in these very low-energy groups was zero, and only the leakage data in the original 199 neutron groups and 42 gamma-ray groups of the original VITAMIN-E data set were used in the radiation transport calculations (Chapter 3). To ensure that the energy spectrum would be well characterized, the output transport calculation was run to a final time of one second.

To further ensure the quality and completeness of the Hiroshima calculations several other significant calculations were undertaken. Prior to calculating the source term for the Hiroshima and Nagasaki detonations, six static uranium critical assemblies, including the Little Boy Replica (LBR) operated as a critical assembly, and three atomic test detonations were used to calibrate and benchmark the LANL calculation. These tests revealed that the detail added to the ENDF uranium cross sections, since the last calculations 20 years ago, has resulted in a closer agreement between the calculations and measurements across all tests. Similarly, the recalculation of the LBR critical-separation experiment improved significantly, resulting in predicting a yield of 16 kt for the Hiroshima device. Further efforts to thoroughly characterize this source term calculation included checking the calculated leakage through the steel case of the Hiroshima bomb against neutron transmission measurements made using through-the-case material at the Los Alamos Neutron Scattering Center (LANSCE) source.

Given the asymmetrical geometry and dense steel nose of the Hiroshima bomb, calculation of the shadowing on the ground created by the 15-degree tilt of the bomb at the time of detonations is important to the accurate characterization of the radiations. Three-dimensional Monte Carlo calculations make it possible mathematically to describe asymmetry (Chapter 2). This correction is particularly important in making accurate comparisons between calculated and measured fast neutron activation. There is little effect from the tilt on thermal neutron activation, and there is no need for such a correction in Nagasaki, where the bomb was symmetrical.

The nominal yield for the Hiroshima bomb has been assessed to be between 12 and 20 kt from previous source-term calculations. This wide range of possible yields is primarily attributed

to not knowing exactly when neutron multiplication began in the bomb. This timing uncertainty was known when the bomb was being designed, so multiply-redundant polonium-beryllium neutron initiators were incorporated to ensure that neutron multiplication would begin at the optimal time during the supercritical configuration of the device. Despite this acknowledged range of possible yields, none of the variations calculated by LANL within the range of design parameters produce a yield below 15 or above 18 kt. The nominal yield obtained from these calculations is 16.1 kt or 7% more than the nominal yield used in DS86.

The geometry and construction of the Nagasaki bomb was significantly different from that of the Hiroshima bomb. The Nagasaki bomb was a symmetrical plutonium implosion device. The neutron and gamma-ray leakages from this geometry are isotropic to within the accuracy of calculations. Unlike the Hiroshima bomb, Nagasaki-type bombs have been tested and measured repeatedly. All of these factors help to define the range of possible yields much more tightly. The nominal yield for the Nagasaki bomb calculated for this reassessment is 21.4 kt within a possbile range of 18 to 22 kt. This calculation agrees with the yield for Nagasaki from nuclear test data for DS86. The verification of these yield calculations is discussed in the section on bomb parameters (Chapter 1). While these calculations suggest no change in the Nagasaki yield and suggest only 7% increase in the yield for Hiroshima, these same calculations produce surprising differences in the gamma-ray outputs for the two bombs.

While there is good agreement in the areas where the DS02 and DS86 calculations overlap, there are significant differences between the two calculations, especially in the total number of prompt gamma rays from both bombs, and in the number and energy of the neutrons produced by the Nagasaki atomic bomb. The Nagasaki output spectra changed substantially from DS86. Compared on the basis of moles per kiloton, there are 43% more gamma rays and 3.4% fewer neutrons escaping from the bomb than were calculated for DS86. At the same time, the average energy of the Nagasaki neutrons is now only 63% of that calculated for DS86. This dramatic reduction in neutron energy and corresponding increase in gamma rays is attributed primarily to the increase in the nitrogen-capture gamma rays that were generated in the calculation by the ability to run the bomb output calculation to “late time” (approximately one second), permitting temporal convergence of the output that was unachievable when the DS86 calculations were run. The ability to not only include the entire goemetry of the bomb in the model, but to run such a complex calculation for this duration was made possible by the massively parallel capacity of the computers on which this 2001 calculation was made. Other factors also contributed to the increase in gamma rays: the improvements in the ENDF/B6.2 nitrogen cross sections used in calculating the nitrogen capture in the high explosive surrounding the critical assembly of the bomb, the use of a 20 MeV upper bound for gamma energy in the calculation rather than the 10 MeV cutoff used for DS86 (which includes the 11 MeV nitrogen-capture gamma rays), the inclusion of all of the metal parts of the bomb in the geometry model used for DS02 (again made possible by increased computer capacity), and the inclusion of a bremmstrahlung source not present in the DS86 calculation. As result of these factors, DS02 calculates more gamma rays for Nagasaki than DS86, and proportionally, more of this increase in gamma rays occurs at energies above 5 MeV, which contribute to survivor dose.

The shift to fewer, lower average-energy neutrons and to more higher-energy gamma rays in the Nagasaki output spectrum is significant. The distinct downward shift in the peak for the thermal neutron energy (see Chapter 2) reflects the increased gamma rays from neutron capture. This shift to lower energies is significant, because neutrons of such low energies have such short

mean free paths that they contribute little neutron flux on the ground. This has the effect of lowering the already-small neutron contribution to Nagasaki survivors doses. The 43% increase in prompt gamma rays is significant because it contributes substantially to the approximately 9% increase in average DS02 Nagasaki gamma kerma. Unlike the Hiroshima bomb, where secondary and delayed gamma rays consitute most of the gamma dose, in Nagasaki prompt gamma rays represent 17% of the total number of gamma rays produced from all prompt, secondary, and delayed sources. Thus, the increase in Nagasaki gamma kerma is a direct result of the increase in the number and energy of the gamma rays in the DS02 bomb output calculation. While most of this increase in DS02 gamma dose is produced by the additional nitrogen captures at late times in the calculation, the presence of all of the metal bomb parts in the DS02 calculation contributes to the gamma-ray production, as does the bremsstrahlung source, and the improvements in the metal and oxygen cross sections in ENDF/B6.2 .

In Hiroshima, there is a similar increase in gamma rays from the DS02 output calculation, but no decrease in either total neutrons or neutron energy. Gamma-ray leakage increased by 31%, while total neutrons escaping from the bomb remained unchanged compared to the DS86 calculation. In Hiroshima, the increase in gamma leakage is attributed to improved resolution in the cross sections, including those for iron and uranium, which were not factors in Nagasaki. While the ENDF/B6.2 cross sections had a similar effect on the gamma leakage from both bombs, the material in the bombs, the radiations escaping from the bombs, and the radiation doses resulting from those bombs are not the same. For example, the steel surrounding the fissile core of the Hiroshima bomb did not downscatter the neutrons generated in the explosion as did the hydrogen and nitrogen-rich high explosives in the Nagasaki device. This results in many more energetic neutrons escaping the Hiroshima explosion and many more energetic gamma photons escaping the one in Nagasaki. The gamma leakage from the Hiroshima device accounts for no more than about 4% of the total gamma rays. The majority of the Hiroshima gamma-ray dose is produced from secondary gamma rays generated by capture reactions and delayed gamma-ray emmisions from the radioactive debris. Once all prompt, secondary and delayed raditations have been accounted for, the new Hiroshima output spectrum increases the total free-in-air kerma by an average of 7% for survivors between 1,000 and 2,500 m from the hypocenter, due primarily to the 6% increase in yield. Unlike Nagasaki, the Hiroshima neutron kerma increased by an an average of 9% over the distances from the bomb where most survivors are located.

Thus, the impact of the new source term calculations is to increase Nagasaki gamma dose by approximately 10% while reducing all neutron doses by 5 to 30% (an average of 17%). In Hiroshima, total and neutron doses increase by 8 to 9%. Whereas the overall increase in dose for most survivors is less than 10%, there is a net change of 25% between the neutron doses for Hiroshima and Nagasaki. Because neutron doses are numerically small, it would be expected that any changes in radiation risk would be equivalently small. Whatever the outcome, the results can be based on a source term derived from the first three-dimensional calculation of the complete bomb geometry, calculated with continuous-energy cross sections to sufficiently long times to fully chacterize the output spectrum from the explosions.

Prompt Radiation Transport Calculation

In order to carry out radiation transport calculations after detonations, it is necessary to know the angle and energy dependent distributions of the prompt neutron and gamma ray leakage from

the weapon. These are obtained by originating the radiation transport calculation with the output leakage spectrum generated by the LANL calculations. When combined with the yield and height of burst for the detonation, these become the basic input parameters for the air-over-ground transport calculations. Because the evolution of radiations during transport from initial to final state is dependent on the materials with which the radiations interact during transport, one must also know the composition of the local environment, including the air density and humidity, as well as the ground surface composition of water and trace elements that would absorb or scatter the radiation. Using these parameters, the next step in the dose reconstruction calculation is to account for the nuclear fate of the prompt radiations as they are transported from the surface of the bomb through air and over the surface of the cities to the locations where survivors are located. This is accomplished in discrete ordinates radiation transport (DORT) and Monte Carlo air-over-ground calculations conducted at the Oak Ridge National Laboratory (ORNL).

The DORT methodology derives its name from the replacement of the continuous angular variable by weighted values for discrete angles, such that particles are only allowed to scatter along a finite number of directions rather than in all directions. The discrete representation of the spatial and energy variables in the discrete ordinates transport equation is obtained by dividing the geometry into a fine space mesh and by using multigroup cross sections. The result is a numerical integration that produces highly differential solutions to the Boltzmann transport equation. The ORNL DOORS 3.2 code system was used for the discrete ordinates transport calculations in this reassessment.

The air-over-ground environments for Hiroshima and Nagasaki were modeled in cylindrical geometry in which the altitude extended to 2,000 m and the radius to 3,000 m with 130 mesh intervals. The prompt radiation transport calculations were performed using an air-over-ground geometry, where the weapon was presumed to detonate over a completely flat homogeneous ground surface. This geometry is highly idealized and, obviously, does not represent the actual landscape-surface environment. No account is made in the prompt radiation calculations for buildings, houses, bridges, terrain variations or other structures that may have affected the behavior and consequences of the radiation or nuclear responses. Analyses to include these effects as well as the effects of topographical features are handled in separate shielding calculations.

These discrete ordinates calculations were performed using the ENDF/B6.2 multigroup cross-section data described in the documentation of the VITAMIN-B6 fine group neutron-gamma-ray cross-section library constructed using 199 neutron and 42 gamma-ray energy groups. There are now 36 thermal energy groups in the neutron data, including upscatter with 5.043 eV as the upper boundary. This expanded number of neutron and gamma ray energy groups represents a considerable improvement over the total of 46 neutron groups and 22 gamma-ray groups used for the DS86 study. The DORT calculation was run to achieve 10^{-3} convergence in the collided fluence for all neutron and gamma-ray energy groups.

At the completion of the DORT transport sequences, the uncollided and collided neutron and gamma-ray fluences were summed to obtain the total fluence distributions for the event. The VISTA code (DOORS3.2, 1998) was used to format the GRTUNCL-DORT data for use in forward-adjoint processes for combining data for the prompt and delayed radiation and for performing building, house and other shielding calculations. Spatial and angular dependent fluences calculated using the discrete ordinates methods were combined with delayed neutron and gamma-ray fluences for use in shielding calculations.

Delayed Radiation Calculations

Delayed radiation is generated from the emission of neutrons and gamma rays from fission products in the fireball of the detonation. The blast creates low-density air within the fireball that enhances the transport of these radiations, producing a large contribution to the radiation fluences. As such, the delayed radiations from the Hiroshima and Nagasaki bombs contribute approximately half of the gamma-ray doses to survivors. Delayed radiations are at least 30% and as much as 60% of the total Nagasaki free-in-air dose depending on distance from the epicenter. In Hiroshima, delayed radiations are between 44% and 60% of the total dose. Delayed radiations are almost entirely gamma rays, with neutrons contributing less than 0.5% to the dose of survivors. Overall, delayed gamma rays represent roughly half the free-in-air tissue kerma generated in Hiroshima and Nagasaki.

The delayed radiation reported in DS86 was recalculated in 1993 and again in 2002 for this study using transport codes and methods described in Part B of Chapter 3. The results of the 1993 delayed neutron calculations and the results of the delayed gamma calculations carried out in 2002 are used for the delayed radiation fluences in DS02. All of the inputs and calculation codes used in DS02 changed from the delayed calculations done for DS86. The DS02 calculations used the LANL ENDF/B6.2 spectra based on fission product yields rather than the augmented maxwellian and empirical spectra used in DS86. The DS02 delayed transport was done with modern DORT air-over-ground code using ENDF/B6 cross sections rather than the ENDF/B5 cross sections used in DS86. The time dependent geometry of the fireball for both DS86 and DS02 was done with somewhat different versions of the STLAMB hydrodynamic code. This code, which calculates the location of the fission debris source within the fireball, is the only part of the DS02 detonation calculation not done with three-dimensional geometry. The funding for the current reassessment did not support a three-dimensional hydrodynamics calculation. Nevertheless, evaluation of the results of the delayed calculations done during DS86 and current comparisons with nuclear test shot results show agreement within the uncertainties of the measurements. Given that the location of the debris source within the fireball is very difficult to predict, and therefore somewhat uncertain, a future state-of-the-art 3-D hydrodynamics calculation of the two detonations would serve as a useful check on this aspect of the DS02 calculation.

Radiation Measurements

The radiation measurements from materials present in Hiroshima and Nagasaki at the time of the bombings provide one of the primary methods for the evaluation of the calculations that comprise the radiation dose reconstruction system. The first radiation measurements were made in Hiroshima, within weeks of the bombing in 1945, measuring the fast neutron activation of ^{32}P (half-life of 14.3 days) in sulfur that was used as an adhesive for insulators on electric power poles (Chapter 9, Part A). Subsequently, other kinds of radiation measurements were made in both cities. Since the 1960s, quartz inclusion, high temperature, and pre-dose thermoluminescence (TL) techniques have been used to measure gamma rays in ceramic materials such as roof tiles and bricks (Chapter 7, Parts A and B). Thermal neutron measurements also began in the 1960s with the measurement of activation in cobalt (^{60}Co; half-life of 5.3 years), followed in the 1980s by the beginning of europium (^{152}Eu; half-life of 13.3 years)

measurements. Cobalt-60 measurements were initially made by counting beta decay particles and have been made more recently by counting the 1173- and 1333-keV gamma rays emitted during ^{60}Co decay (Chapter 8, Part A). Europium-152 gamma- and x-ray spectra measurements have been made in samples of roof tiles, rocks, concrete, and brick using heavily shielded germanium [Ge(Li)] and x-ray detectors (Chapter 8, Part B). At the completion of DS86, these were the measurements available with which calculations could be compared.

While a sufficient number of TL measurements had been made to permit meaningful comparisons with the DS86 calculations, the same was not true for neutron activation. This was especially true of the fluence monitors for the fast neutrons emitted directly from the bombs, because the relatively small number of sulfur measurements made in Hiroshima in 1945 were the only fast neutron measurements ever made. No fast neutron measurements have ever been found for Nagasaki. This lack of a sufficient number of *in situ* measurements that could be confidently used as neutron fluence monitors led to the initial uncertainty about the neutron calculations in DS86 and to subsequent efforts to provide such measurements. Since 1986, scientists have made over 300 trace radiation measurements using existing techniques and over 150 measurements using new methods developed specifically for the study of Hiroshima and Nagasaki.

Given the decay time for radioisotopes since 1945, activation in material irradiated by bomb neutrons has decayed to extremely low or immeasurable levels. By 1986, bomb-induced ^{60}Co had decayed to levels that were very difficult to measure, even with long-term counting in an extremely low-background counting facility. The only other measurable thermal neutron product available at the time was ^{152}Eu. In 1986, there was no available assay that could be used to evaluate the fast neutron activation that had been measured in the short-lived ^{32}P measured in Hiroshima during the weeks following the bombing. This situation prompted efforts to make ^{60}Co measurements while it was possible to do so, and to make as many ^{152}Eu measurements as possible. It also created the motivation to identify new activation products that could still be used as *in situ* fluence monitors for bomb neutrons after fifty years. Because long-lived radioisotopes, with their very low count rates, can only be detected using mass spectrometry, efforts to develop accelerator mass spectrometry (AMS) techniques applicable for Hiroshima and Nagasaki samples were undertaken as DS86 was being concluded.

In 1987, German scientists demonstrated that ^{36}Cl from Hiroshima could be measured using accelerator mass spectrometry (AMS). During the same year, American scientists made AMS measurements of ^{36}Cl from four sites in Nagasaki that agreed with the neutron activation calculated there. Since that time, investigators in the U.S, Germany and, more recently, Japan have continued to make AMS ^{36}Cl measurements, so that there are now 140 ^{36}Cl measurements from 40 sites in Hiroshima.

Thermal neutron measurements do not measure bomb neutrons directly. Thermal neutrons are generated as fast neutrons from the bomb interact with elements in the environment, particularly the ground, producing ^{36}Cl, ^{60}Co and ^{152}Eu. Energetic bomb neutrons incident on a material lose energy to elements in the material by scattering until the neutrons become slow or thermal neutrons, which undergo neutron capture by elements such as chlorine, cobalt or europium, producing the radioisotopes whose activity is counted in thermal neutron measurements. The resulting thermal activation is a reflection of the energy spectrum of the incident bomb neutrons. However, the resulting activity can be significantly influenced by the water and hydrogen content of sample material, which dominates thermal neutron absorption in soil (Chapter 10, Parts E and F). The activation can also be influenced by the other elements present in the neutron path within

the material such as silicon and potassium, and trace elements such as cadmium, dysprosium, gadolinium, lithium, boron, and samarium, which can have significant cross sections for thermal neutron absorption (Chapter 10, Parts C and D). Similarly, the local environment surrounding the sample (Chapter 10, Part B) influences thermal neutron activation, whose composition, moisture and trace elements can moderate the level of activation. Making such measurements from "found" materials a half-century after the bombing is difficult at best, and is subject to many not-fully-understood factors that can influence the results and their interpretation. Such difficulties led some measurements to be interpreted as supporting a "neutron discrepancy" in the late 1980s and early 1990s. A better understanding of these difficulties, and measurements specifically designed to define the limits of *in situ* activation measurements has led to the resolution of this apparent discrepancy. Thus, it has always been highly desirable to have a measure of activation by fast neutrons directly from bomb, despite the fact these activation levels are subject to elevation by cosmic rays (Chapter 9, Part D) and global fallout.

Two approaches to measure nickel-63 (^{63}Ni; half-life of 100.1 years) in copper samples exposed to bomb neutrons were developed by 1994: an accelerator-mass-spectrometry (AMS)-based approach (Chapter 9, Part B), and a low-background scintillation counting approach (Chapter 9, Part C). These techniques provided the means to obtain new fast neutron measurements. Further, using an ultra-pure separation technique and a tandem accelerator fitted with a gas-filled magnet, AMS measurements provided the sensitivity required to measure samples at greater distances from the bomb than the ^{32}P measured in 1945. Six AMS measurements and one low-background scintillation measurement of ^{63}Ni were made from Hiroshima samples for this reassessment. No ^{63}Ni measurements were made in Nagasaki because no suitably pure copper sample was identified despite the evaluation of several samples. Other copper samples, located in Hiroshima after the completion of this reassessment, have also been measured and will be reported separately.

In 1986, the TLD gamma-ray measurements were in sufficient agreement with the calculations to justify the adoption of DS86 by RERF. There was no important discrepancy between the limited number of Hiroshima ^{32}P fast neutron measurements and the DS86 calculations. The small number of ^{152}Eu measurements available at that time was sufficiently uncertain to prevent them from confirming the calculations. The ^{60}Co measurement disagreed with the DS86 calculations by an ever-increasing factor that was five at 1,000-m distance from the Hiroshima hypocenter. In Nagasaki the existing measurement data were scattered and lacked the accuracy needed to confirm the calculations. Despite confidence in the ability of DS86 to predict the gamma dose for survivors, which represents more than 95% of the radiation in Hiroshima and Nagasaki, the inability to definitively confirm the calculated neutron dose using *in situ* measurements stimulated scientists to make additional neutron activation measurements in the years following the adoption of DS86. Given the inability to make fast neutron measurements at that time, all of the neutron measurements made between 1986 and 1993 were of thermal neutrons activation in ^{36}Cl, ^{60}Co, or ^{152}Eu.

Within a year of the adoption of DS86, new europium and chlorine measurements were being made. Japanese investigators repeated ^{152}Eu measurements of Hiroshima samples after radiochemical purification of samples. Seventy new unshielded samples of granite, concrete and roof tiles (Chapter 8, Part B) were collected and measured for europium activation. American investigators began making ^{36}Cl measurements in concrete (Chapter 8, Part D). These new ^{152}Eu and ^{36}Cl data revealed the same systematic discrepancy as had been observed previously in the

Hiroshima ^{60}Co data. This observation, which broadened the perception that there was a neutron discrepancy in Hiroshima, led directly to more chlorine measurements made in Germany (Chapter 8, Part E), Japan (Chapter 8, Parts D and E) and the U.S. (Chapter 8, Part D), and to more Japanese europium measurements, as well as to the development of the AMS ^{63}Ni assay for fast neutrons (Chapter 9, Part B).

As mentioned earlier in this summary, when this reassessment began, there was no commonly held idea of what caused the neutron discrepancy, or how it could be remedied, or that it could, in fact, be remedied. Thus, the reassessment began with a concerted effort both to make ^{63}Ni measurements and to recalculate the bomb. When the total recalculation of the Hiroshima detonation, with its many improvements, failed to remove the discrepancy at more than 1,000 m, and emerging ^{63}Ni measurements agreed with both the 1945 fast neutron measurements (^{32}P) and the calculations, the Joint Working Group shifted focus to the thermal neutron measurements and to the quality-control experiments that provided the critical evidence needed to resolve the discrepancy between distant thermal neutron measurements and calculations.

The Japanese Working Group proposed and organized a set of three quality-control measurements combined with sample-specific DS02 calculations for ^{36}Cl and ^{152}Eu to address the observations that: (1) the ^{152}Eu measurements were larger than DS86 calculations beyond about 1,000 m and (2) the ^{36}Cl data measurements near the hypocenter were about 30% lower than either the DS02 calculations or the ^{152}Eu measurements (Chapter 8, Part H). The protocols for this series of measurements were agreed to by the scientists making measurements from Japan, Germany and the U.S at a joint Hiroshima workshop in November 2001. The measurements, carried out in 2002, involved the efforts of scientists at Hiroshima University, Kanazawa University, Tsukuba University, the Technical University and the Ludwig Maximilians University of Munich, the Lawrence Livermore National Laboratory, and the University of Utah. Sample-specific calculations for chlorine and europium were carried out at Science Applications International Corporation (SAIC) and Kyoto University.

The first set of measurements was to re-measure previously measured granite samples for ^{152}Eu using the ultra-low-background germanium detectors in the Ogoya Underground Laboratory at Kanazawa University, where background levels were about 40 times less and the detection efficiency was about three times greater than in the previous measurements (Chapter 8, Part I). In previous ^{152}Eu measurement, 344.3 keV gamma rays could only be detected from samples collected within 1,000 m of the Hiroshima hypocenter and within 600 m of the hypocenter in Nagasaki due to limitations on sample size. To address this problem, the samples for re-measure, taken from distances of 134 to 1,177 m range from the Hiroshima hypocenter, had ten times the mass of the previous granite samples. Control samples taken from locations between 1,385 and 8,791 m from the hypocenter were also included in this study (Chapter 8, Part I).

These Kanazawa University measurements demonstrated that the previous discrepancy between measured and calculated ^{152}Eu at distance beyond 900 m were due to the inability to properly evaluate the 344.3 keV peak caused by interference from 342.7 keV gamma rays produced by ^{227}Ac background, which is not produced by activation from bomb neutrons. Additionally, the use of the Ogoya germanium detector with twice the energy gain of the germanium detector used previously improved the counting statistics for the 344.3 keV gamma peak in samples collected more than 1,000 m from the hypocenter, where the ^{227}Ac interference is most significant. These results were enhanced by the consistently large size of the raw bulk

samples and by special, high-purity chemical enrichment of ^{152}Eu performed by a contract laboratory at the Japan Chemical Analysis Center. The results from this low-background re-measurement of ^{152}Eu demonstrated that the activation detected in previously measured samples beyond about 900 m from the hypocenter in Hiroshima was significantly influenced by background radiation. These new measurements closely match the DS02 calculations to a distance of approximately 1,400 m from the Hiroshima bomb, where counts from background begin to significantly interfere with the ability to confidently attribute ^{152}Eu activation to bomb neutrons. These results, in combination with the adjustment of the Hiroshima HOB to 600 m, place the ^{152}Eu results in excellent agreement with the DS02 calculations from the hypocenter to the point where activation from bomb neutrons can no longer be distinguished from background, supporting the DS02 calculation and effectively resolving any discrepancy between calculations and ^{152}Eu measurements.

The other parts of measurement quality-control studies were intercomparisons among the three laboratories making AMS ^{36}Cl measurements, followed by the comparison of those results to the Ogoya europium measurements and site-specific calculations. The first of those intercomparisons was designed to control for inter-laboratory variability in sample preparation. This was done by preparing and irradiating standard solutions of europium and chlorine at Hiroshima University, distributing them for measurements to the three laboratories conducting AMS ^{36}Cl measurements, Tsukuba University in Japan, the Technical University and the Ludwig Maximilians University of Munich in Germany and the Lawrence Livermore National Laboratory in the U.S. The standard solutions, which contained 1,000 ppm of europium and chlorine, were irradiated with either thermal neutrons obtained by shielding the Hiroshima University ^{252}Cf fission neutron source with nylon, or irradiated with epithermal neutrons obtained by shielding the same source with Newlite. The results indicate good agreement between laboratories, with average Cl/Eu ratios of 1.08 for thermal neutron measurements and 0.91 for epithermal neutrons (Chapter 8, Part H).

Given the agreement among labs in making standardized measurements, the Joint Working Group undertook to determine whether there was consistency among the three laboratories in preparing and conducting AMS measurements of chlorine. To accomplish this, the labs measured ^{36}Cl in aliquots of the same nine samples in which ^{152}Eu was measured at Ogoya. This permitted not only an intercomparison of the results from laboratories making AMS ^{36}Cl measurements but also provided a way to determine whether or not the ^{36}Cl and ^{152}Eu measurements made from aliquots of the same Hiroshima sample agreed. After the measurements were complete, each was compared to a site-specific DS02 calculation. In measurements of the same samples, the laboratories making AMS measurements of ^{36}Cl have small variations from one another, but these measurements envelop the DS02 calculation out to a slant range of 1,100 m from the bomb. Adjusted for the thermal transmission factors (Chapter 8, Part J), the site-specific calculations for the samples measured in this intercomparison agree very well with these intercomparison measurements. Over the range covered by this series of measurements, the slope of the DS02 calculation is in close agreement with the slope of these measurements. Converted into ^{36}Cl-equivalents for comparison, the ^{152}Eu measurements made from these same samples are in general agreement. While the intercomparison ^{152}Eu measurements are slightly greater than the calculations and the ^{36}Cl measurements are slightly less than the calculations, the slope of both of these sets of measurements is in close agreement with the DS02 slope. In general, these intercomparison measurements are in agreement out to 1,400 m slant range from the Hiroshima

bomb, after which the ^{36}Cl measurements have too much variability to accurately match DS02 and the ^{152}Eu results (Chapter 12, Part D).

Taken as a whole, the Hiroshima ^{36}Cl measurement in granite and non-surface concrete are consistent with DS02 from the hypocenter to distances where the ^{36}Cl/Cl ratio becomes indistinguishable from background, at about 1,400 m. Analysis of the many ^{36}Cl measurements and calculations that have been made during the last 15 years has produced several insights. Serial measurements into concrete core samples taken from Hiroshima buildings strongly suggest that meteoric chloride can penetrate into cement, increasing the measured activation on and in the first few centimeters below the surface. This is also supported by the observation that elevated ^{36}Cl levels have been measured in surface cement samples at distances well beyond the range of bomb neutrons in both Hiroshima and Nagasaki. Granite has shown to be less affected by this meteoric chloride exchange than cement. Based on the extensive work presented in Chapter 8, Part D, it is now clear that the high ratio of measured ^{36}Cl to that calculated by DS86 for samples more than 1,400 m from the Hiroshima bomb resulted from the use of surface cement samples, which have a higher background than non-surface concrete or granite samples. These observations led to the conclusion that bomb neutrons did not produce high level surface measurements.

There are still differences in the methods that different laboratories use to account for and subtract background from their ^{36}Cl measurement. Background for the Japanese measurements of ^{36}Cl in granite ($1.6 \pm 0.5 \times 10^{-13}$) at Tsukuba University is based on the measurement of distant control samples (Chapter 8, Part F). German ^{36}Cl/Cl ratios were determined in granite samples exposed to atomic-bomb neutrons in Hiroshima and in reference granite samples not exposed to atomic-bomb neutrons ($0.6 - 0.7 \pm 0.09 \times 10^{-13}$). For the distant granite samples, German scientists calculated the *in situ* production of ^{36}Cl by cosmic rays and neutrons originating from the decay of uranium and thorium (Chapter 8 Part G). Those calculations led the Munich group to conclude that, within experimental uncertainties, no significant discrepancy is found between measured ^{36}Cl/Cl ratios and those based on DS02 calculations at ground ranges greater than 800 m, if the natural concentration of ^{36}Cl in the granite samples is taken into account. For smaller ground ranges, evidence was found that experimental fluences derived from ^{36}Cl are lower than those based on DS02 calculations (Chapter 8, Part E). The background for U.S. ^{36}Cl measurements ($1.24 \pm 0.3 \times 10^{-13}$) was obtained from deep concrete samples, leading U.S. measurers to conclude that, when surface samples are excluded, the U.S. ^{36}Cl measurements in both Hiroshima and Nagasaki agree with DS02 (Chapter 8, Part D). The background values used by the different labs reflect not only different scientific judgements about the way to establish background, but different materials (including different kinds of granite), different laboratory practices in sample preparation, and the measurements with different laboratory backgrounds using different cyclotrons. Those differences not withstanding, ^{36}Cl measurements no longer offer any evidence of more bomb neutron activation at distance than is calculated by the DS02 Dosimetry System.

Cobalt-60 Measurements

Given the effective resolution of the discrepancy between the calculations and the europium and chlorine measurements, the Working Group considered it important to address the ^{60}Co discrepancy, because it was the only apparent discrepancy noted in the DS86 report and the only

remaining thermal neutron measurements left to be reconciled with the calculations in the current reassessment. While a number of ^{60}Co measurements were made before the completion of DS86, 40 new Hiroshima and 30 new Nagasaki measurements were made subsequently. Thus, it was thought important to determine whether new measurements and the many changes and improvements in DS02 would also bring the ^{60}Co measurements into agreement with the calculations as well. The new measurements were consolidated with the measurements made prior to DS86 for this analysis.

The primary source of ^{60}Co data available for testing DS86 neutron calculations was the Japanese National Institute Radiological Sciences (JNIRS) measurements done in the 1960s. In 1987, Japanese scientists from Hiroshima University measured cobalt activation from Hiroshima and Nagasaki. Between 1988 and 1993 both American scientists at ORNL and Japanese scientists from the Japan Chemical Analysis Center and the Japan Radioisotope Association measured cobalt activation in two sets of samples taken from 692-m and 1,283-m ground range from the Hiroshima hypocenter. Over the decade from 1992 to 2002, other scientists in the nuclear engineering program at Hiroshima University measured cobalt activation in an extensive set of samples from both Hiroshima and Nagasaki. In 2001, a number of these Hiroshima University samples were re-measured in the underground Low Level Radioactivity Laboratory at Kanazawa University. In 1997, more Japanese measurements were made from rocks located near the hypocenter at Nagasaki. Scientists at Hiroshima University addressed the problem of determining peak counts versus background counts at very low count rates from distant samples. In the U.S., scientists from the Environmental Measurements Laboratory and ORNL addressed the extremely difficult problem of saturated ^{60}Co activity in steel from cosmic rays and other environmentally produced neutrons (Chapter 8, Part B). Some corrections were made to previously published data. The ground ranges of all measurements were reviewed, and new ground ranges were determined when possible by transforming sample coordinates to new Hiroshima and Nagasaki city maps. Transmission factors were evaluated and calculated where possible. Experimental measurements of ^{60}Co background activity from environmental neutrons was reviewed and found not to be an important factor in the measurement of bomb-induced cobalt activation in either city.

Analysis of the all the available ^{60}Co results indicates that raising the burst height in Hiroshima from 580 m to 600 m eliminated the over-calculation of ^{60}Co activation at ground ranges less than 500 m from the hypocenter, producing excellent agreement between the calculations and the close-in measurements in Hiroshima. The under-calculation of ^{60}Co at ground ranges of more than 1,000 m has been shown to be a problem of distinguishing between sample activity and background. There is now good agreement between measured and calculated ^{60}Co activation out to a ground range of 1,300 m in Hiroshima with one exception; the JNIRS measurements in the iron ring samples, where the specific activity appears to be too large due to either counter calibration or counter operation. The changes to the parameters for the Hiroshima bomb effectively remove the “contradiction” of the calculated values by the cobalt activation measurements. The factor-of-five disagreement between the measured and calculated ^{60}Co activation noted in the DS86 report has been resolved. For the approximately 100 ^{60}Co measurements in Hiroshima, the weighted measured-to-calculated ratio (M/C) for DS02 is 0.96 with a 46% standard deviation. While there were no new measurements or reanalysis of older Nagasaki ^{60}Co measurements for DS02, these measurements are generally consistent with the DS02 calculations, despite considerable scatter in the data. The weighted M/C for the approximately 35 ^{60}Co measurements in Nagasaki is 1.11 with a 46% standard deviation. With

the resolution of the thermal neutron discrepancies, it is important to consider the agreement of the fast neutron and gamma-ray measurements, which are the bomb radiations most directly related to survivor dose.

Fast Neutrons

Sulfur Activation Measurements

Sulfur activation measurements from the $^{32}S(n,p)^{32}P$ reaction are more easily related to the neutron leakage from the bombs than the thermal-neutron activation of other materials such as cobalt, europium, and chlorine, because high-energy (fast) neutrons, such as those escaping from the bombs, are required to activate sulfur. As such, sulfur activation measurements have been useful in refining and verifying the neutron source-term calculations for the Hiroshima bomb during both DS86 and DS02.

In September 1945, two survey teams, one from the Physical and Chemical Research Institute (Riken) at Tokyo and the other from Kyoto University, collected sulfur samples in Hiroshima that had been used to adhere porcelain insulators to electrical power poles. Because ^{32}P decays by the emission of very energetic beta particles (E_{max} = 1.71 MeV), it can easily be measured using very simple instruments with a thin aluminum window over a detection chamber. The Riken group measured beta-particle ionization intensity from one-gram samples of sulfur using thin-window Lauritsen electrometers. The measurements of the Kyoto University survey team were made by pulse counting of individual beta particles from the sulfur samples using a thin-window Geiger-Mueller (GM) counter. Until the recent AMS ^{63}Ni measurements, those of ^{32}P were the only fast neutron measurements available from the atomic-bomb detonations in Japan. No equivalent sulfur activation measurements were found for Nagasaki. However, the activation of both sulfur (fast neutrons) and gold foils (thermal neutrons) has been measured at tests of Nagasaki-type weapons.

For the current reassessment, the locations of the sulfur samples were updated for the new hypocenter location, and for sample location, if that was in error (Chapter 9, Part A). The distance from the epicenter of the Hiroshima detonation to the sample location was adjusted for the 600-m HOB, and the sulfur activation was re-evaluated using the DS02 parameters, including the 15-degree tilt of the bomb (Chapter 2).

The use of the DS02 parameters brings the ^{32}P measurements into agreement with other Hiroshima data. After the current re-evaluation, the sulfur activation measurements are as well established as the data permit out to 500-m ground range (800-m slant range) from the bomb. The ^{32}P measurements are consistent with DS02 out to a slant range of 800 m. Beyond 900-m slant range, the measurements are too uncertain to be used to evaluate the DS02 calculations. The DS02 increase in yield and HOB compared to DS86 decreased the calculated sulfur activation and brought the ^{32}P measurements and calculations into better agreement. These changes also brought the yield estimate derived from sulfur activation measurements within the range of possible yields calculated by LANL for the Hiroshima bomb. The addition of the tilt factor to the calculations reduced the variability in the ratio of the measurements to calculations by about 20%, increasing not only the overall agreement between the sulfur activation measurements and calculations, but increasing confidence in those data as well.

Copper Activation Measurements

The development of methods to measure ^{63}Ni from copper in the early 1990s utilizing the ^{63}Cu(n,p)^{63}Ni reaction was important because the 100-year half life of ^{63}Ni made it possible to measure fast neutron activation 50 years after the bombings, allowing comparison of current measurements with those made years ago. These techniques opened up the possibility of making fast neutron measurements to distances of approximately 1,800 m from the bomb, where copper activation and background become indistinguishable, well beyond the 500 m ground range where the sulfur activation measurements are fully trusted. Copper samples from six different locations at 391 to 1,470 m from the hypocenter in Hiroshima were measured for ^{63}Ni activation by a team of U.S. and German scientists (Chapter 9, Part B). Japanese scientists measured one sample located at 1,501 m from the Hiroshima hypocenter using liquid scintillation counting (Chapter 9, Part C). To date, no measurable copper sample has been located in Nagasaki. Three line-of-sight samples obtained a few hundred meters from the Nagasaki hypocenter were determined to be composed of an alloy with approximately 4,500 ppm of nickel, which is much too high for useful fast neutron information from ^{63}Ni.

The ^{63}Ni measurements made between 900 and 1,500 m are the first fast neutron measurements in Hiroshima to be made at distances from the bomb where survivors are located. Accounting for background in these ^{63}Ni measurements has been difficult. Background was measured to be 7.26×10^{-4} at about 1,800 m from the Hiroshima hypocenter using AMS. Background concentrations of ^{63}Ni in samples not irradiated by the bomb neutron fluence, whether from natural (e.g., cosmic ray) or other unidentified sources, have not been measured using liquid scintillation. Therefore, all investigators used the AMS measurements to subtract background from the ^{63}Ni measurements. Calculations of cosmic-ray induced ^{63}Ni in copper (Chapter 9, Part D) have not fully accounted for the higher background measured in copper samples. It is possible that the ^{63}Ni background measured in copper samples may come primarily from sources such as the sample chemistry, the sample holders, and the AMS machine. Nevertheless, when measured background is subtracted from the ^{63}Ni measurements and the values are adjusted for activation decay since 1945, the Hiroshima copper activation measurements are in good agreement with DS02 sample-specific calculations out to 1,600 m slant range from the Hiroshima hypocenter, one measurement notwithstanding.

The slopes of the ^{63}Ni measurements and DS02 calculations are in close agreement except for the sample taken from the Bank of Japan at 391 m from the hypocenter where the measured value is somewhat less than one standard deviation lower than the DS02 calculation. Elsewhere, the ^{63}Ni measurements agree with the site-specific DS02 calculations. Although the measured result at the Bank of Japan is somewhat below the calculated value, the difference does not approach statistical significance given the uncertainties involved, even if the uncertainty of the free-in-air ^{63}Ni activation versus distance as calculated by DS02 is considered (Chapter 9B). In fact, the ^{63}Ni measurements are consistent with the slopes calculated for both DS02 and DS86 out to a ground range of 1,500 m from the Hiroshima hypocenter. However, these copper activation measurements are in better agreement with the DS02 yield and HOB than with the parameters used for DS86 (Chapter 9, Parts B, C, and D).

Thus, these new fast neutron measurements confirm the 1945 sulfur activation measurements and are consistent with the background-corrected thermal neutron measurements. Both sets of fast neutron measurements support the elevation of the Hiroshima height of burst to 600 m and

the yield to 16 kt. Together with the agreement achieved for the background-corrected thermal neutron measurements there is broad support for the conclusion that DS02 is a good and accurate calculation of the neutron doses from the Hiroshima bomb. Thus, the overall agreement achieved between both the fast and thermal neutron measurements and the DS02 calculations effectively resolves the Hiroshima neutron discrepancy.

The resolution of this discrepancy is comprised of the myriad improvements made in the dosimetry system, but it was dependent on three fundamental changes. First, the agreement between the calculations and the thermal neutron measurements at distances of more than 1,000 m from the bomb is dependent on the recognition and correction of unaccounted-for background in those measurements. Second, correcting the height of burst for the Hiroshima bomb to 600 m brings the measurements and calculations under the bomb into agreement. Third, the reevaluated yield of 16 kt brings the measurements and calculations in Hiroshima into better overall agreement. Thus, the neutron activation measurements are as well accounted for by the DS02 calculations as is reasonable to expect from the present state-of-the-art for a dose reconstruction of this complexity.

Thermoluminescence Measurements of Gamma Rays

The accuracy of the gamma dose is central to the accuracy of the dosimetry system because most of the dose to survivors is from gamma rays. In Hiroshima the free-in-air gamma kerma is 95% of the total radiation dose for survivors at 1,000 m from the hypocenter. At 2,500 m, gamma rays contribute about 99% of the total dose. In Nagasaki gamma rays comprise 98% of the dose at 1,000 m and essentially the entire dose at 2,500 m. In DS86 the agreement between the calculated and measured gamma-ray doses was good. It remains so in DS02 even though the average gamma dose increased by 7% for Hiroshima survivors and 9% for survivors in Nagasaki, as discussed earlier in this summary. Despite the agreement between the thermoluminescence measurements of gamma rays (TLD) and the DS86 calculations, further TLD measurements have been made in Hiroshima since DS86. Two Japanese groups made TLD measurements in order to utilize the latest TLD techniques and to add resolution to the TLD background. The group at Nara University of Education and Hiroshima University made TLD measurements in Hiroshima, while the group at the Japan National Institute of Radiological Sciences (JNIRS) made measurements in both cities (Chapter 7, Part A).

In Hiroshima, the overall agreement is somewhat better for DS02 than for DS86, largely due to the change in the Hiroshima yield. For DS86, the measurements were overall 7% higher than the calculations. For DS02, averaged for all distances, the measurements agree with the calculations. The agreement of the Hiroshima TLD measurements and DS02 calculations near the hypocenter is excellent. Agreement at middle and longer distances in Hiroshima is better for DS02 than for DS86, although there remain some indications of measured values exceeding calculated values at longer distances. The reasons for these differences, which are probably related to background, are discussed in detail in Chapter 7, Part B.

Although the overall TLD agreement is good in Nagasaki, the measured values tend to be somewhat less than calculated values, at least out to about 800 m from the hypocenter, slightly more so for DS02 than for DS86. The comparison of measured and calculated values in Nagasaki is considerably more difficult than in Hiroshima due to the limited number of measured sites and questions about the applicable transmission factor for most of the sites where DS86 and post-

DS86 measurements were made. Of the four Nagasaki measurement sites at less than 1,400 m from the hypocenter, the measurements at three sites have unresolved questions about the wide range of the measured values on the same type of sample at the same location. There is also concern about our ability to calculate an accurate estimate of a TF that applies to all of the measurements at a given site. Presently, with no adjustment for sample annealing, saturation or possible shielding of the sample, overall Nagasaki TLD measurements are 20% lower than the DS02 calculations. When these adjustments are maximized, the Nagasaki TLD results are 7% below DS02 (Chapter 12, Part D). A number of possible causes in both the measurements and calculations have been considered in an effort to fully account for the Nagasaki TLD results. It is possible that unaccounted-for partial frontal shielding has affected some Nagasaki measurements. It is also possible that the Nagasaki yield, 5 kt greater than Hiroshima, and detonated 100 meters lower in altitude, could have either annealed or saturated the TLD sample materials close in to the Nagasaki hypocenter. These issues are discussed in Chapter 7, Part B.

There may also be the need to reconsider the adequacy of the current delayed source-term calculation. Given that more than half the gamma dose comes from the delayed radiations emanating from the fireball created by the explosion, an error in this calculation could affect the gamma dose more than a similar error elsewhere. Because funding was not available during this reassessment to repeat the fireball hydrodynamics calculation using a modern three-dimensional code, this calculation was made with the same type of two-dimensional code used from DS86. Some members of the Working Group believe that repeating the hydrodynamics calculation with a state-of-the-art three-dimensional code, coupled to the new three-dimensional output from the Nagasaki bomb, could better define the position of the delayed radiation source and the resulting gamma dose from the detonation.

Despite lack of agreement in Nagasaki TLD results that was achieved in Hiroshima, the agreement between calculated and measured TLDs is well within 10%. Using DS02, RERF no longer a finds a statistically-significant cancer risk between the two cities. The results from this first application of DS02 confirm recent DS86 findings that there is no statistically significant city difference in the estimated cancer risk, removing the need to explain such a difference in term of radiation differences in the two cities. Thus, despite areas where potential improvements could still be made in Nagasaki, the DS02 calculation is in good overall agreement with measurements and provides a good basis for the estimation of survivor doses.

Many refinements of DS86 were essential to achieve the degree of agreement in the neutron and gamma measurements and calculations seen in DS02. However, the myriad improvements made in calculations and measurements would not have been able to achieve the high level of agreement achieved in DS02 without significant refinements in the determination of exact location of samples, the detailed documentation of samples, and calculation of a transmission factor for each one. Given that all the refinements in sample calculation and measurement can be rendered useless by the mis-location or placing it at the wrong distance from the hypocenter, the work to refine these elements of the RERF measurement database and to reconcile the distances on the maps used for sample location were equally important.

The RERF Measurement Database

Beginning within weeks after the bombing and continuing until the present, samples of materials from Hiroshima and Nagasaki have been collected for radiation measurements. Over

years, these samples have been collected and documented by first the Atomic Bomb Casualty Commission (ABCC), and in recent years primarily by RERF and two groups at Hiroshima University: the Radiation Information Center of the Research Institute for Radiation Biology and Medicine and the Graduate School of Engineering. Samples have also been collected elsewhere by individual investigators for study over the years.

The types of samples taken for analysis were determined by the measurement technology to be used. The measurement of gamma rays relied on quantifying the thermoluminescence from ceramics such as roof tiles. On the other hand, a number of different materials from sulfur to granite and copper have been used as neutron fluence monitors, depending on the radioisotope being measured. For measurements to be useful in the evaluation of calculations, the measured material must have been present at the time of the bombing, its exact location and composition must be known, and the sample must still retain a measurable radiation signal. Because of these requirements, efforts to carefully and fully document the material composition, location, and shielding of samples have been ongoing for sometime.

Chapter 4 of this report describes the collection of measurement samples and their documentation that are available in the RERF Dosimetry Measurements Database. A complete listing and documentation of all of the sites from which samples have been measured are included in this report. Where possible, it also provides cross-referencing to the excellent collection of detailed materials about buildings and other sites that are published in books by the Hiroshima Peace Memorial Museum and the City of Nagasaki by giving the site reference numbers. Each sample site is identified by an auto-sequence number, a building identification number, material, sample point number, sample type sequence number, RERF identification number, new city map X and Y coordinates, ground distance, height above ground, elevation of ground level relative to that of the hypocenter, and the identities of investigators to whom samples have been supplied for measurements.

In addition to the information in the database, RERF maintains site drawings, annotated maps, and other materials such as aerial photographs, and photographs of the sample-collection sites for samples collected after DS86. This detailed collection has been essential in verification, correction, and reassessment of measurements used in the DS02 reassessment. Given that the usefulness of a measurement is no better than the accuracy with which that sample can be located in relationship to the source of the radiation, all aspects of the relationship from detonation point to sample location were reassessed for DS02, and upgraded where possible. The existence of this measurement database in its present form is due in large measure to two scientists who unfortunately did not live to see the completion of this report. Dr. Shoichiro Fujita designed and originated the RERF Database. Mr. Wayne Lowder suggested and initiated the efforts to consolidate the various measurement databases.

Alignment and Referencing of Maps and Aerial Photographs

Of all of the information cataloged concerning a measurement sample, the ability to accurately determine the distance of that sample from the radiation source is the most important factor for dose reconstruction. In Hiroshima and Nagasaki, those distances are established from maps of the cities on which the location of given samples and that of the hypocenter is plotted. Given the pivotal importance of accurately establishing sample locations in their use as checks on calculations, special effort was made in the DS02 reassessment to reconcile the differences

between current and World War II maps with regard to the location of the radiation sources and the measurement samples. Chapter 5 details the process undertaken to transform the locations of the hypocenters and measurement samples from the historically used World War II U.S. Army maps to newer more detailed city maps using Geographic Information System (GIS) technology and to verify the results.

The new maps of Hiroshima and Nagasaki were reconciled with World War II maps by georeferencing control points that could be unambiguously located on the maps both before the bombing and in 1979-1981, when the Japanese developed the current more detailed maps. Twenty-three landmarks in Hiroshima and nine in Nagasaki, such as massive buildings or mid-river points on bridges that could be documented from the historical records and clearly located on aerial photographs available at RERF, were used as control points for the DS02 GIS reconciliation of the old and new maps. This alignment of the two sets of maps did not produce a change in Hiroshima hypocenter on the U.S. Army map, but did shift the corresponding hypocenter position on the newer Japanese map about 15 m to the west. In Nagasaki, the hypocenter on the new map shifted only about 3 m west of the previous location. This reconciliation of hypocenter locations on the maps of the two cities was a vital first step in removing as much uncertainty as possible from the measurements. However, it should be noted that while the new hypocenter locations were used in DS02 to calculate the distances to all of the measurement samples, RERF has not yet begun to use the new Japanese maps to estimate survivor distances. This will be done as part of plans to migrate the survivor data to a new GIS-based system. Currently, the RERF measurement database contains both the old and new distance data.

Transmission Factors

Transmission Factors (TFs) are calculated in order to relate the measured radiation in a sample to the free-in-air kerma levels given in Chapter 3. Neutron transmission factors account for the modification of fluence and activation at the location of each *in situ* sample. For DS02, TF is defined as the ratio of the sample activation divided by the FIA activation at a height of one meter above the ground at the same ground range. Thermal neutron TFs are affected by several different parameters: sample height, shielding of the sample by surrounding material, shielding by other structures or objects, neutron energy cross sections, isotope or isotopes producing the measured isotope, and composition of the material. Thermal neutron TFs and the procedure for their calculation are described in Chapter 8, Part J. In order to calculate the TFs for fast neutrons, the additional parameter of the tilt of the bomb has to be taken into account for Hiroshima. The TFs for ^{63}Ni and the procedure for calculating them are given in Chapter 9, Part E.

Transmission factors for TLD measurements were obtained differently. Because new calculations of *in situ* dose to quartz in TLD samples were not performed for DS02, it was necessary to develop a method to apply the DS86 calculations to both the new gamma-ray and neutron fluences of DS02 and to the samples that were not calculated in DS86. The definition of TFs for TLDs rests on the assumption that the angle and energy distributions of the incident (free-in-air) gamma-ray fluences at the sample locations are similar enough in DS86 and DS02 that the transmission factors would be the same. Therefore it was assumed that the overall effect of scattering and attenuation of DS02 gamma rays would be adequately approximated by using the ratio of the calculated *in situ* dose and FIA kerma for DS86 to approximate the ratio of

calculated *in situ* dose and free-in-air kerma for DS02. The methods used to calculate the angle of incidence and the TFs for TLDs are described in Chapter 7, Part B. Just as it is essential to account for all of the attenuation of FIA kerma in determining the radiation dose from an isotope within an *in situ* sample using TFs, it is essential to account for the moderation of the FIA kerma by the intervening body tissues in order to accurately determine the dose absorbed by specific tissues of survivors.

Survivor Dosimetry

The purpose of the dosimetry system at RERF is to provide the radiation dose absorbed in the tissues of survivors. The DS02 radiation dose is the energy deposited in any of 16 different tissues in survivors (absorbed dose), which is calculated from the free-in-air (FIA) tissue kerma modified by the appropriate soft-tissue fluence-to-kerma conversion coefficient or kerma coefficient. RERF Dosimetry Systems do not calculate survivor doses using transmission factors as is done for *in situ* measurement samples, rather DS86 and DS02 use an organ spectrum database made up of thousands of Monte Carlo transport histories connecting the energy-angle radiation fluences to the energy response in specific organs.

The total FIA tissue kerma from neutrons and gamma rays changed less than 10% from DS86 to DS02. At ground distances of 1,000 and 2,500 m where most survivors are located, the DS02 total FIA tissue kerma increased in Hiroshima by an average of 7%. Over the same range of survivor distances from the bomb, the Nagasaki total FIA tissue kerma increased by an average of 9% (Chapter 12, Part B). These changes result primarily from the increase in output calculated for the bombs.

The kerma coefficients used in the calculation of absorbed dose were upgraded as part of the DS02 reassessment. Because there had been refinements in the data used in the coefficients since these coefficients were established for DS86, a new evaluation was completed for DS02. The DS02 evaluation considered the changes in the composition of soft tissue of the body recommended in ICRU Report 44, the latest mass energy-absorption coefficients for photons, and the revised elemental kerma coefficients for neutrons contained in ICRU Report 63. This evaluation indicates that the differences between the DS86 and DS02 kerma coefficients are small for the neutron and photon energies most important for survivor dosimetry (Chapter 12, Part A).

The differences in organ doses between DS86 and DS02 generally reflect the changes in the FIA tissue kerma as expected. Given that the differences between DS86 and DS02 were less than 10%, the DS86 body shielding and organ dose database modules of DS86 could readily be adapted and applied to DS02. No changes were required to the organ dosimetry routines used in DS86. While the changes in organ dose are small for DS02, the values are not identical to those in DS86. Three factors contribute to the differences. First, the kerma coefficients were changed by a small percentage, as described in Chapter 12, Part A. Second, the increase in computer capacity now permits the use of a larger organ spectrum database containing approximately ten times as many particle histories, permitting RERF to obtain the particle spectrum and dose inside the organ with much less uncertainty. Third, because the organ spectrum database is made up of thousands of Monte Carlo histories connecting the energy-angle radiation fluences to the energy response of an organ, changes in the energy or angle of the incident fluence can change the organ dose. The slight changes in DS02 are most significant for the prompt and delayed neutron fluence, and result from spectral changes in the free-field kermas (Chapter 12, Part C).

Survivor Shielding

The dose to most atomic bomb survivors is affected by the shielding provided by a wooden structure in which the survivor was located or which was between the survivor and the detonation. Typically, this shielding is adequately accounted for by assigning a survivor to a shielding category and applying the appropriate transmission factor for that shielding category to the dose. Since DS86 was installed, some shielding problems, exceptions and omissions have been identified.

Shortly after DS86 was implemented at RERF, several shielding categories were found to have a bias or excessive uncertainty. This was corrected at that time. In 1989, a large bi-modal uncertainty was identified for the shielding category where there was no neighboring house in the direction of the bomb, closer than twice the height of the survivor's house. However, other neighboring houses still provided additional frontal shielding for the survivor. This was remedied in DS02 by subdividing the category for survivors with no frontal shielding into three sub-categories that better define the survivor's location, and by separating the shielding leakages according to new rules (Chapter 11, Part B). This change to the nine-parameter shielding changes the doses for the affected individuals in the new categories with most and least frontal shielding beyond two house heights by about -15% and +10%, respectively. It was found that the dose for individuals in large open wooden structures, such as schools or gymnasiums, was low by about one third when the building models were modified for the number and distance between interior walls. This was corrected in DS02 by increasing the gamma dose by 35% within such structures calculated using the DS86 house models. Globe shielding is applied to survivors in the open who were shielded by Japanese houses and to survivors in the open shielded by terrain features. This method uses the globe data to infer a survivor's position from a series of street and terrain positions. The radiation field for the survivor is then calculated using an adjoint method to couple leakage data with the free-field fluence to compute the dose to a survivor at that position. It was found that the uncertainty in globe shielding calculations could be reduced from 21% for a single calculation to about 15% by averaging a number of neighboring shielding positions. In this way the uncertainty is related to the number of shielding calculations done to obtain the dose. This shielding modification, which was implemented as part of DS02, reduces the shielding uncertainty obtained by the globe method to an uncertainty more like that obtained using the nine-parameter method applied to most of the survivors (Chapter 11, Part B).

The shielding produced by large terrain features such as mountains was not included in DS86. To address this, the shadow shielding provided by Hijiyama Mountain in Hiroshima and Konpirasan Mountain in Nagasaki was evaluated (Chapter 11, Part C). Comparisons between benchmark calculations done in Hiroshima using the Monte Carlo Adjoint Shield (MASH) code and the simplified geometry of the upgraded DS02 terrain-shielding model produced comparable results. This simplification was made possible because the grazing angle of the mountain ridge toward the hypocenter was the important parameter in determining the transmission factor in the shadow of the mountain. In Hiroshima the shadow extends 150 m beyond the peak or 25 m beyond the base of Hijiyama Mountain, which affects about 50 discrete survivor locations. The effect of the mountain on the transmission factors disappears by about 200 m from the base of the mountain. The higher Konpirasan Mountain in Nagasaki produced a 900-m shadow extending into the middle of the valley behind the mountain, affecting about 200 discrete survivor locations. Several nearby peaks cast shadows that vary in length from 800 to 1,300 m. In general, TFs for

gamma rays are reduced about twice as much as the TFs for neutrons because the gamma rays tend to be propagated more in a line-of-sight path from the bomb than neutrons. In order to implement this, RERF obtained high quality digital elevations for Hiroshima and Nagasaki, enabling them to calculate the five required grazing angles for each affected survivor location. Affected survivors have been re-coded as terrain shielded and their dose calculated using DS02. It is estimated that this change reduced the transmission factors for terrain-shielded Nagasaki survivors in these shielding calculations by about 30%, but had little effect overall on the TFs of terrain-shielded Hiroshima survivors.

The shielding for the workers in the Nagasaki heavy industry factories is unlike the shielding for the other survivors in the RERF Life Span Study. Unlike persons who were in wooden Japanese houses, or in the open, even those shielded by a mountain at the time of the detonation, the workers in the Nagasaki factories were in large structures made of quite different material than the material in houses. The factories contained many large metal objects that provided significant partial body shielding for some of the workers, making the exact location of an individual in relation to local shielding material crucial to the accurate dose assessment for that individual. There is also some uncertainty as to whether or not the roof of the building collapsed or was blown off by the blast wave prior to the arrival of the delayed radiation, which constitutes at least 50% of the dose that those factory workers received. Recent comparisons between the doses for those individuals derived from RERF chromosome aberration data and DS86 calculations suggest the DS86 doses received by many Nagasaki factory workers may have been overestimated by as much as 40% relative to those for other survivors in Japanese houses and other shielding configurations. Because the factory workers represent about 25% of the Nagasaki survivors with DS86 doses in excess of 0.5 Gy, any systematic error in their dose estimates can have a substantial impact on the risk coefficients derived from RERF studies.

The doses to factory workers could be in error for many reasons, all due to the many uncertainties in their unique surroundings at the time of the detonations. When this reassessment began, the Joint Working Group was aware of this special case and undertook a study at Oak Ridge National Laboratory (ORNL) to see if better accounting for the unique shielding in the factory buildings could be the cause of this apparent discrepancy. For these detailed calculations, the model of the factory building, its internal structure, machinery and tools were considered. However, changes in the distribution of the shielding elements within the factory relative to the survivors following the blast wave were not considered.

An initial scoping study was conducted at ORNL to see if the density of the materials present in the factories could produce a dose reduction of the order of magnitude suggested by the biological dosimetry. This study, using a simplified model of the materials in a typical workbench, was found to reduce the tissue kerma by about 40%. The results of this scoping study were sufficiently encouraging that the calculation of doses of a representative subset of the factory workers was undertaken to determine whether such a calculation could resolve this issue.

In this study, ORNL calculated the FIA kerma for 40 representative factory workers using a three-dimensional model of the factory and the same DORT and MASH code used for transport and shielding calculations in this reassessment. The torpedo assembly factory (Building 22) was selected from the 25 buildings in the Mitsubishi complex because it was documented in sufficient detail in the 1946-47 USSBS Reports to permit it to be modeled, and it contained 307 of the 1,041 factory workers in the Life Span Study. At a nominal 1,350 m from the hypocenter and similar in construction to other building containing survivors, it was considered to be the best model for the

extrapolation of results to the remainder of the factory workers, whose doses were not calculated in this study. Unfortunately, the dose reductions derived from the calculations of Building 22 were not enough to account for the apparent discrepancy in the doses to those survivors. Overall, the dose reductions provided by the factory shielding averaged about 8%. Because this reduction only affected survivor locations behind benches and those located far from the factory wall closest to the hypocenter, factory-worker TFs were reduced on average by only about 3% relative to other survivors in Nagasaki not affected by shadow shielding from mountains. The initial risk analyses done by RERF using DS02 continue to indicate a difference in risk estimates for those factory workers.

There are many factors that could contribute to a failure to account properly for the reconstructed doses in this most complex environment of the entire atomic-bomb dosimetry system. The location of the survivors is a potential source of error. In an analysis done after this work was completed, it appears that Building 22 is located some 11.5 m farther from the hypocenter on the georeferenced aerial photographs than was used either in these ORNL calculations or in DS02/DS86 calculations using the RERF survivor location database. This difference in location, however, would only result in a 5% reduction in dose for those survivors. More important is the location of survivors in relation to large steel objects such as torpedoes and heavy machinery that would provide partial body shielding. Partial body shielding not only makes the calculation of dose more complex, it is currently not addressed by the RERF dosimetry. Partial body shielding can also significantly affect the chromosome aberrations used for biological indication of dose for comparison with calculated doses. Neither the shielding details nor the resources were available for the ORNL calculations to permit the kind of analysis needed to resolve these issues for 40 survivors, let alone all 1,041 of the factory workers.

It is possible that the level of detail necessary to adequately model the shielding of each factory worker does not exist in the historical record. It is also crucial to know the status of the roofs of the factories prior to the arrival of the delayed radiation because the presence of the roof changes the gamma-ray transmission factor by about 20%, resulting in a net change of 3% in the total gamma dose. Some Working Group members have suggested that the hydrodynamic portion of the delayed radiation calculation could position the radioactive fission fragments too low in the fireball, increasing the delayed gamma dose and thus contribute to this apparent discrepancy. This unresolved issue in the doses to factory workers and the observation that overall gamma doses in Nagasaki are calculated slightly higher than measured led some to conclude that the height of the debris source in the fireball would be a potential remedy to both problems. Given that the hydrodynamic portion of the fireball calculation is one of the most uncertain aspects of a nuclear explosion and that this calculation is the only portion of the DS02 reassessment done with same type of two-dimensional code used for DS86, the calculation of the fireball hydrodynamics with a modern three-dimensional code coupled to the three-dimensional output calculation would seem justified. While DS02 has improved the shielding for Nagasaki factory workers, it has not resolved the apparent discrepancy in their doses. Pending further work, the doses for the Nagasaki factory workers cannot be established with the same confidence as doses for the other survivors.

Uncertainty Analysis

The DS86 Dosimetry System was criticized for lack of a systematic quantification of uncertainties in dose estimates. The Committee on Dosimetry for the Radiation Effects Research Foundation of the U.S. National Research Council specifically recommended that any revision of the RERF Dosimetry System should undertake a complete evaluation of uncertainty for all stages of the system for dose determination and such an uncertainty evaluation should become an integral part of any new dosimetry system. The DS02 reassessment includes an analysis of the components contributing to both the systematic and random uncertainties in assigning doses to survivors (Chapter 13). Thus, DS02 provides a dose and associated uncertainty estimate for each survivor.

In order to make DS02 uncertainties as defensible and credible as possible, this analysis contains not only uncertainties in individual computational elements and radiation dose components, but it also describes how these relate to comparisons between observed and computed quantities at critical intervals in the computational process. Comparisons are made between the observed and calculated radiation for free-field thermal neutrons, fast neutrons and gamma-ray thermoluminescence, which are relevant to the estimated systematic uncertainty for DS02. The comparisons also include those between calculated and observed survivor shielding, where the observations consist of biodosimetric measurements for individual survivors, which are relevant to the estimated random uncertainty for DS02.

Like DS86, the DS02 Dosimetry is a modular, wholly computational system comprised of independent components. DS02 begins with the free field transport of the neutron and gamma-ray leakage from the bomb through air, through and around structures and terrain, producing a shielded radiation field that culminates with transmission into the body and computation of mean radiation fields and doses in individual organs. An advantage of such a modular computational approach is that it permits the overall dose uncertainty to be estimated, based on a combination of constituent uncertainties associated with each computational element and radiation dose component. The uncertainties of individual components in each computational element are inferred from input parameters, reaction cross sections, computational methods, computational statistics, assumptions made in creating the computational description of the events and on expert judgment, derived from information contained in the DS86 and DS02 final reports. Another advantage of the modular computational approach is that it permits the differentiation of the uncertainties into two types, “systematic,” describing the likelihood that doses to all individuals in a given city will increase or decrease together, and “random,” affecting each individual survivor more or less independently. The disadvantage of using uncertainties inferred for individual computational components to estimate an overall uncertainty value is that the result may be at odds with gross empirical observations. This was the primary criticism of DS86 uncertainty estimates, where small uncertainties were obtained for the neutron calculations, while there was a large discrepancy between those calculations and the *in situ* measurements.

In DS02, an assessment of uncertainty has been made for the source, free-field radiation, house-shielding and body-shielding elements of the system. The correlation of uncertainty between survivors in the same and different cities has also been assessed, providing the basis for categorizing uncertainty contributions as random or systematic. The assessment has been constructed to accommodate propagation of uncertainty through each element of the system, including a provision to account for correlation between uncertainties associated with various

radiation components. The statistical model incorporated in the system makes no assumptions concerning the probability distribution of the uncertainty values. The model is designed to calculate the uncertainty associated with the mean dose to a specific organ of a single survivor, where the mean dose is calculated as the mean kerma within each organ volume. Total dose is the sum of dose from eight radiation components: prompt neutron dose, fission product (delayed) neutron dose, early (prompt and air/ground secondary) gamma-ray dose, fission product (delayed) gamma-ray dose, prompt neutron-house secondary gamma-ray dose, delayed neutron-house secondary gamma-ray dose, prompt neutron-body secondary gamma-ray dose, and delayed neutron-body secondary gamma-ray dose. Each dose component has an uncertainty associated with its computed value. This uncertainty is expressed as a coefficient of variation (CV), which is the ratio of the standard deviation of the distribution of the values to the mean value (also called fractional standard deviations or FSD in Chapter 13).

For the uncertainty analysis of this report (Chapter 13), each factor contributing to survivor dose uncertainty is described, including how each was derived, and the method for combining the component uncertainties to obtain the estimate of overall uncertainty in survivor dose. The estimated uncertainty value obtained for each factor that contributes to dose uncertainty, along with that of its associated correlation coefficient for each radiation component is described. The component uncertainties for this analysis were taken to be the uncertainty estimates of the scientists conducting calculations, making measurement, or analyzing data defining parameters. For this analysis, uncertainty was identified in three different categories. The first describes uncertainties that are highly correlated between survivors at a specific city, i.e., systematic uncertainties. The second describes uncertainties, arising from DS02 methodologies, which are uncorrelated or nearly so from survivor to survivor, i.e., random uncertainties. The third are uncertainties that are associated with the input data to DS02 for each survivor, such as his spatial coordinates and description of his shielding. This category of uncertainty is also assumed to be uncorrelated between survivors. The sources of systematic uncertainty considered for Hiroshima and Nagasaki are: yield, radiation output, air density and moisture together with soil moisture, cross sections, the hydrodynamics model, the fission product source, air transport calculation method, burst height, and the shielding calculation methodology. The sources of random uncertainty due to the DS02 methodology considered are: the hypocenter location, the house model, the phantom model and orientation, and survivor shielding assignment for each shielding category (nine-parameter, globe, regular terrain, irregular terrain, factory, and open). The sources of random uncertainty due to DS02 inputs considered are: survivor coordinates, survivor shielding description of each shielding category, survivor position and orientation recall, and shielding survey recall. The estimated uncertainty for each of these components is included in the analysis.

The results of this uncertainty analysis produce very similar results for systematic uncertainties in the DS02 free-fields in the two cities, approximately 12% for Hiroshima and 11% for Nagasaki. This is a significant change from DS86 (17% for Hiroshima and 13% for Nagasaki at 1,500 m). This decrease in the systematic uncertainty seen in DS02 for Hiroshima is due almost entirely to a decrease in yield uncertainty for the weapon detonated there. The random uncertainty associated with a typical proximal survivor at Hiroshima is approximately 25%, with little difference between DS86 and DS02. The total random uncertainty component for Hiroshima may range between 20% and 41%, depending primarily on the method of shielding assignment. The random uncertainty associated with a similar typical proximal survivor in

Nagasaki is approximately 28%, with little difference between DS86 and DS02, but can range between 25% and 44%, again depending primarily on the method of shielding assignment. The primary reason for the difference in total systematic uncertainty between the two cities is the difference in map coordinates uncertainty.

The total uncertainty of the representative DS02 survivor dose is on the order of 30% in both cities, but can range from 27% to 45% of the total dose. The total uncertainty is dominated by its random components, those due to uncertainties in DS02 methodology and those due to uncertainties in input variables. The random component and hence the total random uncertainty, can vary considerably in DS02 because of the large uncertainty range associated with shielding assignment and, to a lesser extent, phantom materials and orientation. The range of total random uncertainties caused by variations in the shielding assignment component is quite large. On the other hand, the systematic component is relatively static from survivor to survivor and from city to city, due primarily to nuclear phenomena measurement and observations made largely in Hiroshima.

Systematic uncertainties can be evaluated directly by comparing *in situ* observations to calculations of the free-field radiations. For random uncertainty, and hence total uncertainty, it is more difficult to find independent observations that may be used to provide confidence in the assigned uncertainty values. In an effort to provide this type of check for the DS02 uncertainties, the doses to survivors with biological dosimetry were compared to calculated doses. For this comparison, RERF provided the shielding histories, electron spin resonance (ESR) based gamma-ray lingual tooth dose, and the fraction of cells bearing stable translocations from cytogenetic analysis for 41 survivors. Comparisons were made between gamma kerma inferred from observations and those calculated from DS86, DS02, and a combination of DS02 free-field radiation with direct computation of shielding, based on the shielding histories. DS02 represents a distinct improvement over DS86 in terms of comparison with the biodosimetric measurement-based kerma estimates. The variation of kerma implied by variability in the ESR measurements was 28% for DS02, reduced from 48% for DS86. The use of the most accurate shielding calculation, based directly on individual shielding histories, reduces the DS02 variation still further to 20%. In the case of gamma-ray kerma inferred from chromosome measurements, comparisons vary around the DS86 calculation by 65%, compared to about 40% for DS02 and about 22% for the most accurate shielding calculation. This limited trial shows a significant reduction in total uncertainty for DS02 over DS86, an improvement that is largely due to the significant changes made to the nine-parameter and globe shielding calculations. This trial also suggests that the uncertainty in survivor dose could be reduced further by refinements in survivor shielding.

Concluding Observations

This joint reassessment of the RERF Dosimetry System has resolved the Hiroshima neutron discrepancy and, in the process, produced the basis for a new dosimetry system, DS02, on which survivor doses can be more confidently based. Many improvements were made to the RERF Dosimetry System in the course of this reassessment. The overall agreement between both old and new measurements and calculations has been significantly improved. The overall uncertainties in survivor doses have been significantly lowered by raising the Hiroshima yield and by the improvements in survivor shielding. The addition of large terrain features and

improvements in the nine-parameter and globe model reduced survivor dose uncertainty. The reconciliation of the Hiroshima and Nagasaki maps are a direct result of this reassessment, which further reduces dose uncertainty. Much improved calculations of radiation transport and transmission factors, using improved cross sections, have produced much more complete calculations of much finer resolution. Members of the Joint Working Group developed new measurement techniques for neutron activation, and a much better understanding of the issues and techniques involved in making *in situ* measurements. Analyses using DS02 also confirm the observation of the last lifespan update that there is no longer a statistically significant difference between the radiation risk in Hiroshima and Nagasaki. There are fewer questions remaining after this reassessment than there were at the beginning. DS02, which is a significant improvement in the eyes of the members of the Joint U.S.-Japan Working Group that produced it, has been implemented and used to produce risk assessments at RERF. Those results have been used by the U.S. National Research Council in the recently released report on Biological Effects of Ionizing Radiation (BEIR) VII Report. The International Commission on Radiological Protection (ICRP) is using DS02 in its revision of radiation risks. Most importantly, DS02 provides a confident basis for the assessment of direct radiation doses to the survivors in Hiroshima and Nagasaki.

DS02 is a notable achievement in scientific cooperation among more that 30 scientists from three different countries and a number of disciplines that came to this reassessment with many different ideas but emerged in agreement about the sources of problems and their solutions. That process involved rethinking long-held ideas, correcting errors, and finding new solutions. DS02 would not be on the firm footing that it is today without years of effort to perfect both the measurements and the calculations. This reassessment would not have been as complete as it is without the support and funding provided by U.S. DOE well beyond the original congressional mandate. It must also be said that this report would not have been completed without the dedication of a number of Working Group members who have contributed generously of their time and efforts during the last two and a half years. Finally, it must also be acknowledged that this dosimetry system owes much to the scientists who worked on previous RERF dosimetry systems, particularly T65D and DS86, which served as the basis for DS02.