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William E. Loewe

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Lawrence Livermore National Laboratory

PERSPECTIVES ON RADIATION DOSE ESTIMATES FOR A-BOMB SURVIVORS

William E. Loewe

Lawrence Livermore National Laboratory*

Abstract

Four decades after the actual events, quantitative characterization of the radiation fields at Hiroshima and Nagasaki continues to be sought, with high accuracy a goal justified by the unique contribution to radiation protection standards that is represented by the medical records of exposed survivors. The most recent effort is distinguished by its reliance on computer modelling and concomitant detail, and by its decentralized direction, both internationally and internally to the U.S. and Japan, with resultant ongoing peer review and wide scope of inquiry.

A new system for individual dose estimation has been agreed upon, and its scientific basis has been elaborated in the literature as well as in a comprehensive treatise to be published in the Spring of 1987. In perspective, this new system appears to be an unusually successful achievement that offers the expectation of reliable estimates with the desired accuracy. Some aspects leading to this expectation, along with a caveat, are discussed here.

Introduction

The need for estimating radiation dose to specific organs of individuals surviving the Hiroshima and Nagasaki bombings may represent a unique scientific enterprise, in the following sense. There is a strong global public signficance attached to absolute accuracy in these dose assignments at the level of a few tens of percent accuracy, for radiations that occurred in a non-reproducible event of high physical complexity, four decades ago under the extraordinary conditions of war and with little opportunity for contemporary observation. The public significance derives from the fact that the medical records of exposed survivors represent the only body of data relevant to radiation risk evaluation that applies to effects of whole-body radiation on humans, which includes a relatively large statistical sample representing a general population, and for which record details are available on a generally consistent basis.

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This challenge to the physics community has been met over the years with various approaches. One is to use direct analogy from observation of other nuclear explosions, such as the Trinity event in New Mexico and the Ranger Fox event in Nevada for comparison to the radiatively analogous explosion of the "Fat Man" bomb at Nagasaki. (No analogous observed event exists for the explosion of "Little Boy" at Hiroshima.) Another approach is to use the phenomenology of radiation in related situations, such as suspended nuclear reactors, a procedure comprising the primary effort on the previous dosimetry system called T65D ("tentative doses in 1965"). A third approach is to infer radiation levels from subsequent measurements of radiation-affected materials at the actual sites themselves, as has been done by Japanese workers using activated sulfur and cobalt for neutron estimates and using thermoluminescence techniques for gamma estimates. A fourth approach is to analyze and model quantitatively the physical mechanisms that determine radiation levels, at least to the degree required to insure that inferences and analogies are not misapplied and that assumptions are reasonable.

The recently culminated, half-decade program of joint effort by Japanese and American scientists that has lead to the "DS86" ("dosimetry system as of 1986") set of dose assignments, has included the work described in the previous papers of this session. The program was strongly shaped by analysis of physical mechanisms, especially as modern computer capabilities enable detailed investigation, but in fact the program exploited all of the previous approaches, with strong reliance on observation of analogous events for quantitative model validation, and with emphasis on in-situ data, extended and re-interpreted as part of the program, for evaluation of the computer predictions. It is this comprehensive synthesis of approaches, ordered by analysis of physical mechanisms and carried out with the detail made possible by computers, that provides one of the major reasons for investing the results with a high degree of confidence in their essential reliability. An early expression of this kind of synthesis appeared in the archival literature as Ref. 1 and 2. The full expression of this overall approach appears in a comprehensive treatise describing all details of the program, scheduled for publication in Spring of 1987 by the Radiation Effects Research Foundation, headquartered in Hiroshima. Oversight for the joint program was provided by Dr. Eizo Tajima of Tokyo and by Dr. Frederick Seitz of New York, with Dr. Robert F. Christy of Pasadena as Group Leader for the U.S. effort.

Discussion

During the first two decades since the events at Hiroshima and Nagasaki, various estimates based on occasional expert opinion showed revisions that in some cases amounted to an order of magnitude. In 1965, a substantial several-year program, centered on measurements of reactor radiations at the Nevada Test Site (NTS), produced a dose assignment system called T65D which was accepted until 1980, when new estimates were set forth formally and publically which revised assignments by factors of as much as five to ten. The immediate impact was to remove the Hiroshima and Nagasaki data as sources of information on neutron risk. Since 1980, estimates of the radiation field have changed very little, as shown in Figs. 1 and 2, which give (a) free field kermas

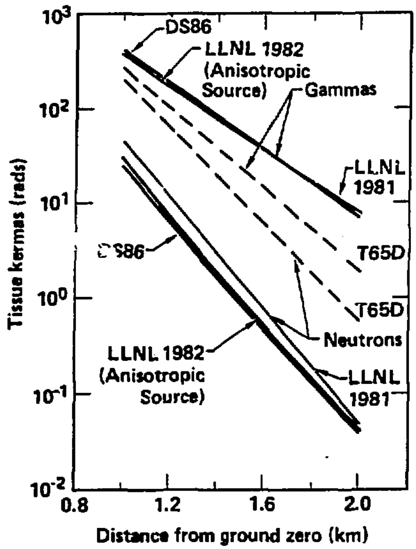

Figure 1. Free-in-air tissue kermas at Hiroshima

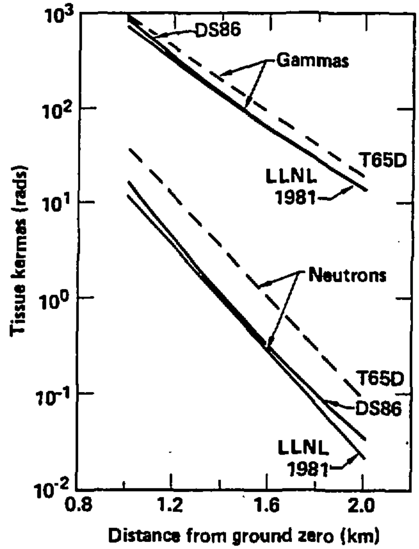

Figure 2. Free-in-air tissue kermas at Nagasaki

obtained as the T65D results, (b) the 1980 results from Ref. 3 with subsequent adjustment in 1982 for anisotropic sources (cf. Paul Whalen in this session), and (c) the DS86 results. Similarly, Table I shows the average house shielding factors for neutrons and gammas at Hiroshima, obtained as the T65D values, the 1980 values given by Jess Marcum of RDA, and DS86 values (cf. W.A. Woolson, et al., in this session). Comparable results are obtained for Nagasaki.

The remarkable feature of Figs. 1 and 2 and Table I, another major reason for high confidence in reliability of DS86 dose assigments, is the small changes brought about by the scrutiny after 1980, in which all aspects of all calculations were repeated and frequently improved, usually in both countries, and validating or supporting observations were carefully re-evaluated and frequently extended. This suggests that methodologies have matured, and that results are not overly sensitive to reasonable assumptions about meterological conditions, so that no large changes are to be expected in the future. In fact, future changes larger than perhaps 10% at a time

Table I

Average Transmission Factors at Hiroshima

Source	Neutron	Radiation Prompt Gamma	Delayed Gamma
T65D	0.32	0.90	0.90
J. Marcum (1980)	----	0.55	0.45
DS86	0.38	0.53	0.46

(and very few of them) are presently regarded by the community as being quite unlikely.

Some special features of the revisions introduced in 1980 were (a) explicit use of meteorology particular to the events, made possible in part by reliance on calculational models validated elsewhere that permitted direct extrapolation to other meterological conditions, and (b) the use of separate components, with models individually validated by experimental data, for gamma dose estimates. Although well-known by specialists to be otherwise, the interested physics community believed in 1980 that the T65D modelling of gamma dose, in which attenuation goes as $\exp(-R/\lambda)/4\pi R^2$, was correct after a short transient distance. In fact, the two major components (coming mostly from neutron capture in atmospheric nitrogen on the one hand, and from fission product debris on the other hand), each have quite different e-folding lengths but similar magnitudes, and can not add up to the T65D form.

An additional special feature was use of detailed radiation leakage intensities as a function of energy for each bomb, made possible by ever-more-detailed calculations at Los Alamos and discussed in this session by Paul Whalen. Figure 3 shows Little Boy spectra for neutrons with energy great enough to penetrate the atmosphere to distances of greatest interest to survivor application. (See Table II as an example of how higher source energies increase in importance with distance.) The bare reactor data represent the basis for the T65D neutron estimates (actually obtained phenomenologically at a reactor), while the remaining curves compare calculation and experiment at the most copiously emitting angle for the static replica as well as the exploding bomb. The 4-5 tons of heavy metal (iron and tungsten) in the gun assembly imply a priori that these data must be roughly right for the bomb, and the replica results confirm accuracy. The small change shown from static to dynamic is to be expected from the fact that first-principle estimates based on reactor physics and sound speeds show that neutrons at these energies are generated and exit well before any major changes in the overall geometry.

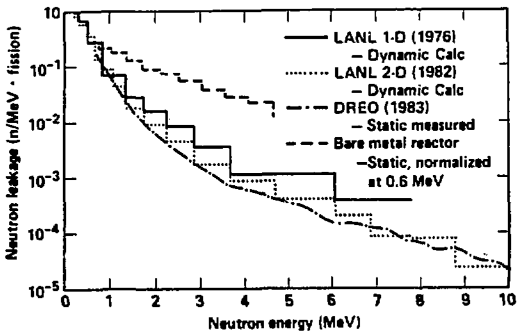

Figure 3. Little Boy neutron leakage energy spectra

Table II

Contribution to Kerma of Source Neutrons ≥3 MeV

Range (km)	Fraction of Total Kerma
1.0	30 %
1.5	50 %
2.0	70 %

(Only neutrons with energies ≥3 MeV can activate sulfur.)

Other 1980 features were (a) extensive reliance on geometrically correct and validated radiation transport calculations, discussed in Ref. 2 and partially abstracted with updates in Table III, and (b) recognition by Jess Marcum of RDA that measured building gamma ray transmissions had been previously misinterpreted. The misinterpretation, whose corrrection generated the changes shown in Table I, resulted from computing transmission factors as the ratio of building interior to exterior measured kermas, even though the interior gamma ray kermas included a substantial contribution from gamma rays generated in the walls by neutrons (which were negligible at Hiroshima and Nagasaki).

Among noteworthy features of the work since 1980, above and beyond the thorough-going scrubbing and scrutiny of all aspects, were (a) construction at LANL of an exact replica of the "Little Boy" bomb (spectral emissions already shown in Fig. 3), and (b) extended and revised estimates of in-situ measurements. These in-situ data include (a) thermoluminescence data discussed by D.C. Kaul in this session, which confirm the essential correctness of the new gamma ray kermas out to half a kilometer beyond data available in 1980 (now to 1 1/2 kilometers from the hypocenter at Hiroshima), and (b) recent data on europium activation, as well as (c) new detailed comparisons between measured and calculated sulfur and cobalt activation. The europium and sulfur comparisons are discussed by M. Gritzner et al., in this session, with bottom lines (a) that data-spread for europium prevents either confirmation or contradiction of calculated low energy neutrons, and (b) that sulfur shows excellent agreement at short distances, implying generally good absolute

Table III

Transport calculations for APRD

Range (m)	Calculated/Measured Neutron kerma	Gamma kerma
100	1.08[a]	1.06
170	1.06[a]	0.91
300	1.30[a]	0.94
400	1.28[a]	0.90
1,080	0.92[a]	0.80
1,618	0.90	0.91

[a]Revised 1984

intensities of neutrons that will subsequently penetrate to large distances of interest (note Table II again), but at distances approaching a kilometer, error bars are too large to permit conclusions about calculated high energy neutron intensities.

Comparisons of calculated and measured cobalt activations, however, thought in 1980 to be in agreement on the basis of simplified calculations, now clearly show major contradictions as depicted in Fig. 4 from Ref. 4. On the one hand, all other comparisons and considerations (including several discussed above) support calculated estimates of higher energy neutrons, and the correctness of then calculating lower energy neutrons is supported by knowledge of physical mechanisms involved as well as by comparison with low energy neutron measurements at the Ranger Fox event (similar to Nagasaki) and at the APRD reactor (which generated the data shown in Table III). On the other hand, these cobalt measurements have been reviewed carefully, and new data obtained at other locations in Hiroshima are entirely consistent with the old.

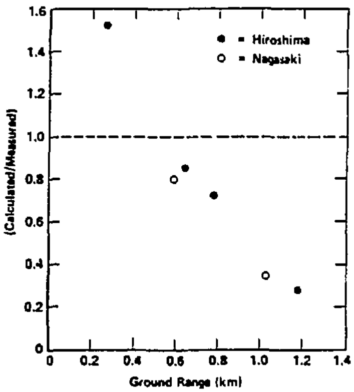

Figure 4. Cobalt activation

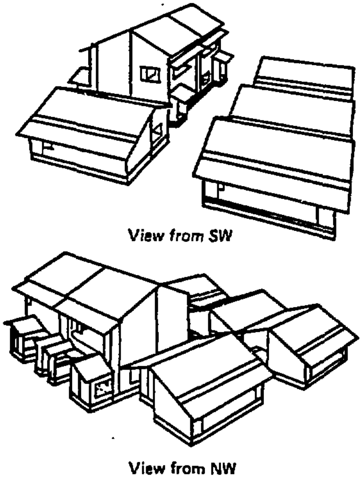

Figure 5. Six-house cluster

Other special features of the work since 1980 include (a) continuing review of explosive energy estimates and benchmarking with the Little Boy replica (no change in yield for Hiroshima and 5 % change for Nagasaki from Ref. 3), and (b) concerted effort to establish bounds on survivor dose from fallout and induced activation, resulting in upper bound estimates for those receiving significant contributions. For that small fraction of the survivors spending much time in those limited areas involved, absorbed doses due to fallout and induced activation are significant but modest.

Probably the most important and certainly the biggest effort since 1980 has been the careful development of detailed, fully consistent and accurate estimates of the shielding provided by both surrounding buildings and by the body itself, as previously discussed at this session by W.A. Woolson et al., and by Steve Egbert of SAI. Based on a long-available 3D method developed by ORNL and validated by SAI, with further validation since 1980 to better than five percent when compared to data from full-scale Nevada mockups of Japanese houses, these estimates result from detailed representation of both geometry and angle-position-energy-dependent physical mechanisms. They give unprecedented realism to estimates of neutron or gamma ray dose to a particular organ of a particular individual located in a particular environment in a specific place, including all known physical contributions. Figures 5 through 8 illustrate the geometrical complexity actually used. Accuracy in these shielding factors, which vary by as much as a factor of three, is believed to be determined by record keeping, not by the estimation process.

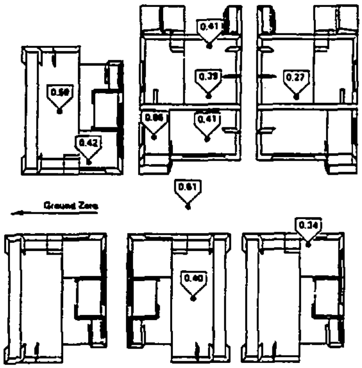

Figure 6. Prompt gamma ray transmission factors

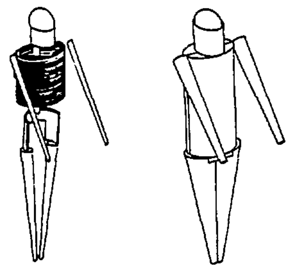

Figure 7. Adult phantom and skeleton

15-year old

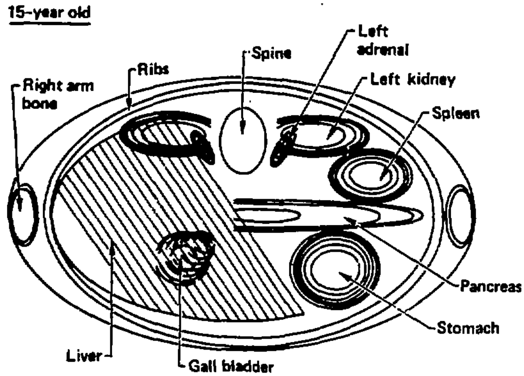

Figure 8. Cross-section of trunk

Conclusions

The current status is that a very complete report supporting the formally accepted DS86 results was prepared in 1936, and a system was installed at Hiroshima for obtaining specific organ doses for particular individuals, which includes the capability of readily accepting any remaining adjustments that may still be forthcoming. A substantial uncertainty analysis is under way, with the objective of providing a quantitative uncertainty attached to every estimated dose; for typical survivors of greatest interest to epidemiology, the uncertainties in dose assignment are expected to be a few tens of percent. This analysis is discussed in papers appearing in the session on Shielding and Radiation Transport Application, II at this conference. Fully consistent application of experimentally validated physics models of all radiation components, with almost no unsupported assumptions, along with extensive evaluation against in-situ data as well as data from other nuclear explosions, has lead the cognizant physics community to invest strong confidence in all of the results; still, there remains one outstanding discrepancy, between measured and calculated in-situ cobalt activation (by thermal and slightly epithermal neutrons). In progress are attempts to (1) reduce data scatter in in-situ europium activation measurements and to (2) resolve differences of expert opinion on the suitability of zircon and uranium-bearing glass samples for fission track analysis; both are independent measures of neutrons similar to those that activate cobalt.

In 1981, intense international interest in the dose revisions was usually expressed to me as the question, "what impact does this have on our understanding of radiation risk", along with expressions of lost innocence in finding that we physicists had previously been so wrong. I like to think that we have now regained much of that lost confidence, and that just maybe the impact will appear first as a shift of some epidemiological data from the class of Rorschach ink blots to the class of scentific evidence, from which new insights may appear.

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