# Chapter 5

# MEASUREMENTS OF NEUTRON FLUENCES

**William E. Loewe and Edgar Mendelsohn**
*Lawrence Livermore National Laboratory*
**Tatsuji Hamada**
*Japan Radioisotope Association*
**Takashi Maruyama**
*National Institute of Radiological Sciences*
**Shunzo Okajima**
*Nagasaki University*
**Joseph V. Pace, III**
*Oak Ridge National Laboratory*
**Masanobu Sakanoue**
*Kanazawa University*
**Sohei Kondo**
*Osaka University*
**Tadashi Hashizume**
*Azabu University*
**Jess Marcum**
*R & D Associates*
**William A. Woolson**
*Science Applications International Corporation*

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Neutrons from the atomic bombs at Hiroshima and Nagasaki made several elements radioactive. Most of this radioactivity decayed away before it could be measured (see Chapter 6). But some did not and can still be measured. The computer programs that are described in this chapter and are being used to reassess the doses of the survivors can also be used to calculate how much radioactivity was produced. The measurements can be compared with these calculations to confirm further the methods of calculation and the accuracy of the cross sections they use.

Some effects other than radioactivity were also produced. For example, Appendix 5-15 and Gold and Roberts[1] discuss the detection of fission tracks in certain materials. These other effects, however, have not yet yielded much information.

Table 1. Ratio of Calculated to Measured Kerma Near a Bare Metal Reactor.

| Distance from Hypocenter (m) | Neutron Kerma | Gamma-Ray Kerma |
|---|---|---|
| 100 | 1.08 | 1.06 |
| 170 | 1.06 | 0.91 |
| 300 | 1.30 | 0.94 |
| 400 | 1.28 | 0.90 |
| 1080 | 0.92 | 0.80 |
| 1618 | 0.90 | 0.91 |

It is important to emphasize at the outset that the ratio of the dose produced (or the biological damage) in tissue to the radioactivity produced in the materials considered below changes considerably with the energy of the neutrons. Thus, comparison of radioactivity measurements with calculations usually tests the accuracy of the calculations in a different part of the neutron energy spectrum than that important for the calculations of dose. In general, however, the tests are of value because accuracy in one part of the spectrum usually implies accuracy in other parts.

It is also important to recognize that there exists a substantial body of excellent neutron fluence and dose measurements for fission sources in air-over-ground geometry that were made at other sites and that these measurements have been compared with calculations made with the same methodology (but not for the same circumstances) as that used here for the dosimetry reassessment. These comparisons of measurements and calculations, which constitute compelling validation of the methodology, are mentioned only briefly here as the observations made in Japan are the chief subject of Chapter 5. However, a brief abstract on the subject by Loewe appears in Appendix 5-1, with pertinent references to published material. A recent comparison is shown in Table 1 where Loewe[2] compares calculations and measurements of kerma in tissue at points in air near the APRD reactor. The two points with 28 to 30% discrepancies are attributed to the presence of trees that were not modeled in the calculations. Most of the rest of the results are within 10%, which is considered state-of-the-art accuracy for these measurements.

This existing validation of the methodology means that the comparisons discussed in this chapter depend only upon circumstances unique to Hiroshima or to Nagasaki (e.g., atmospheric composition, spectrum of emitted radiation, the extraordinary atmospheric effects unique to nuclear explosions) and not upon the quantitative physics of neutron transport through the atmosphere in an air-over-ground geometry.

The following discussion will treat the radioactivities according to the energies of the neutrons principally responsible for them. As explained above, the energies important for production of radioactivity do not always reflect the energies important for production of dose in a person.

## FLUENCES AT HIGH NEUTRON ENERGIES

The only A-bomb-produced radioactivity studied to date that depends on fluences of

**Table 2. Contribution to Kerma in Tissue of Source Neutrons with Energy ≥ 3 MeV. (only neutrons with energies ≥ 3 MeV can activate sulfur).**

| Distance from Hypocenter (m) | Fraction of Total Kerma (%) |
|---|---|
| 1000 | 30 |
| 1500 | 50 |
| 2000 | 70 |

high-energy neutrons is the activation of sulfur, for which there is a threshold near 3 MeV. Neutrons arriving on the ground at these high energies contribute a very small fraction of the total neutron kerma there. However, the lower energy neutrons that contribute most of the kerma are neutrons that were emitted from the bomb at these high energies and lost energy on their way to the ground. Neutrons emitted from the bomb with energies above 3 MeV are especially able to penetrate the atmosphere to great distances. For example, neutrons emitted above 3 MeV contribute half the neutron kerma at 1500 m from the hypocenter (Table 2). At this distance, however, most of those neutrons will have been degraded to less than 3 MeV. Therefore, comparisons of measured and calculated sulfur activations have significance for the dosimetry reassessment, because they are useful in the validation of the calculations.

Yamasaki and Sugimoto (Appendix 5-2) measured the $^{32}P$ produced in sulfur used as an adhesive for insulators on electric power poles. They had samples from close to the hypocenter to about 1000 m ground range. Loewe[3] compared their results to calculations and found fair agreement at the shorter ranges (Figure 1). When measured values of the attenuation in the porcelain insulators were substituted for the values calculated by adjoint methods, the agreement was poorer for reasons that are still not understood.[3] Later, Hamada[4] provided an improved calibration for the Yamasaki-Sugimoto measurements and made uncertainty estimates (Appendix 5-10). Also, Gritzner and Woolson recalculated the activation reported in Appendix 3-5, taking into account the angle to the vertical at which the bomb was falling when it exploded; this tilt made the activation depend on the angular location of the sample point around the hypocenter. These revised sets of measured and calculated data are shown in Figure 2. They show no significant discrepancy between the calculations and estimates at distances to several hundred meters from the hypocenter; beyond that, the measured values are too uncertain to support any strong conclusion on agreement. Taken overall, these comparisons suggest good accuracy for the neutron fluence calculations with energies in the sulfur activation range and at short ground ranges. The accuracy is about the same as that achieved in sulfur activation measurements at the Hiroshima bomb (Little Boy) replica discussed in Chapter 2.

Table 3 compares calculations and measurements of fluences of neutrons above 3 MeV made at the APRD reactor.[5] Accuracy within 10% is again achieved. This accuracy suggests that errors in the calculated neutron kerma at 1500 m of more than some tens of percent would have to be due to neutrons emitted with energies less than 3 MeV. Since neutrons of less than 1 MeV cannot penetrate 1500 m of atmosphere and still contribute significantly to the

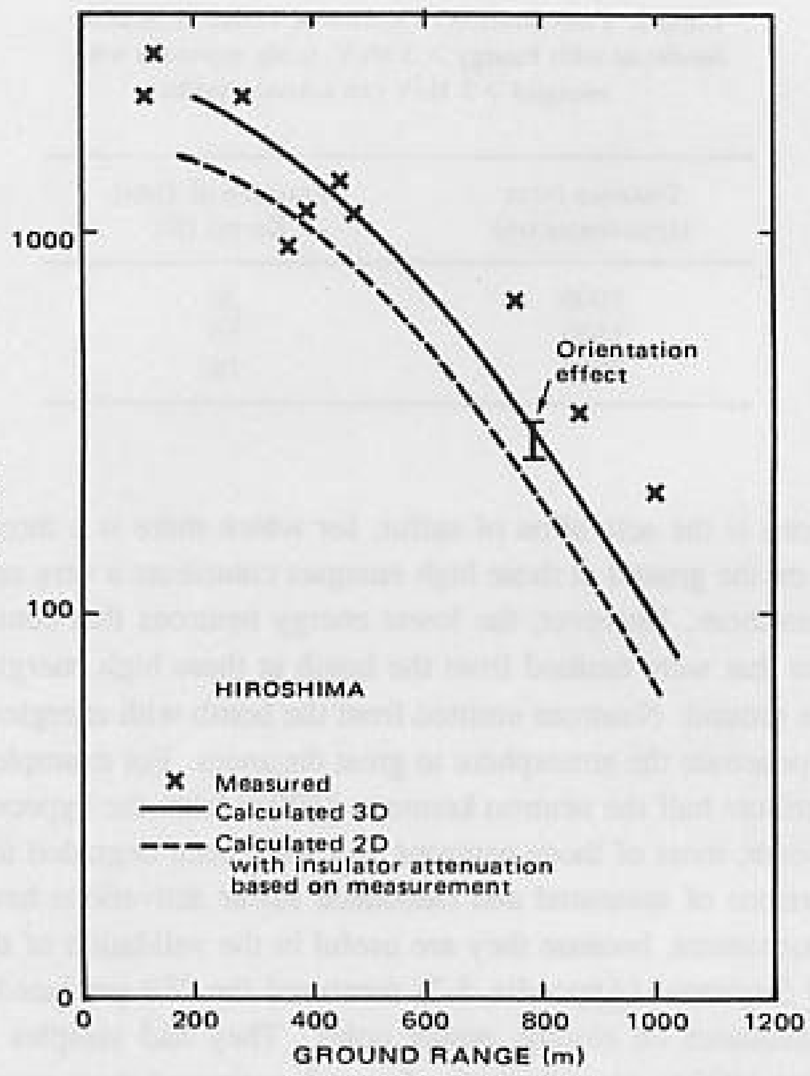
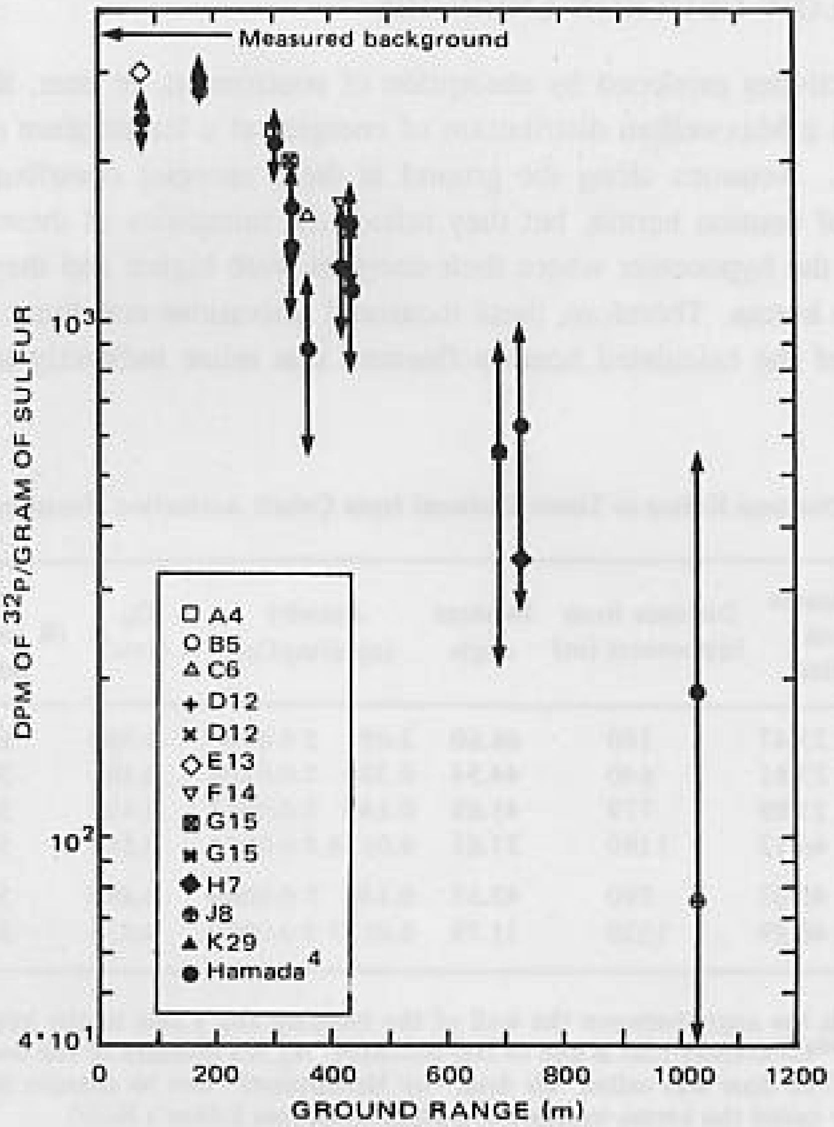



*Figure 1. Sulfur activation at Hiroshima.*

**Table 3. Comparison of Measured and Calculated Neutron Fluences Above 3 MeV at the APRD Reactor.**

| Distance from Hypocenter (m) | Measured ($n/cm^2$ source neutron) | Calculated ($n/cm^2$ source neutron) | Calculated/Measured |
|---|---|---|---|
| 100 | $1.03 \times 10^{-10}$ | $1.01 \times 10^{-10}$ | 0.98 |
| 170 | $2.68 \times 10^{-11}$ | $2.35 \times 10^{-11}$ | 0.88 |
| 300 | $4.07 \times 10^{-12}$ | $3.45 \times 10^{-12}$ | 0.85 |
| 400 | $1.16 \times 10^{-12}$ | $1.08 \times 10^{-12}$ | 0.93 |
| 1080 | $3.74 \times 10^{-13}$ | $3.26 \times 10^{-15}$ | 0.87 |

kerma, it would have to be due to energies emitted with energies between 1 and 3 MeV. Thus, such a hypothetical error would have to be due to some peculiar physical mechanism that interfered strongly with the generation or transport of 1 to 3 MeV neutrons but did not affect neutrons above 3 MeV.




The various symbols are the calculated values for the Yamasaki-Sugimoto measurements listed in the legend on the figure. The filled circles are the Hamada[4] reevaluation of the original data; the uncertainties that he assigned are also shown.

*Figure 2. Comparison of measured and calculated $^{32}P$ activity. Calculation used 15 kt, anisctropic, LANL, Whalen[10] source; new RERF ground zero; 15° tilt to the bomb; 262° degree bomber heading; and 2.5 cm thick porcelain insulator.*

These considerations lead to the expectation that calculated neutron kermas at Hiroshima and Nagasaki are accurate to some tens of percent to perhaps 1500 m, where they have fallen to values approaching insignificance. When this expectation is taken together with similar expectations based on evaluations of source and transport calculations, as discussed in other chapters and in the planned chapter on analysis of uncertainties, present expert opinion is that the calculated neutron kermas at distances of primary interest are accurate to several tens of percent. Nevertheless, this conclusion remains a matter of judgment, not demonstration; and the following discussion of $^{60}Co$ measurements clouds this judgment.

## FLUENCES AT LOW NEUTRON ENERGIES

Several radioactivties produced by absorption of neutrons at, or near, thermal energies (i.e., neutrons with a Maxwellian distribution of energies at a temperature of about 300 K) have been studied. Neutrons along the ground at these energies contribute only a small fraction of the total neutron kerma, but they reflect the intensities of these same neutrons at points closer to the hypocenter where their energies were higher and they did contribute significantly to the kerma. Therefore, these measured activations constitute evidence to use in an assessment of the calculated neutron fluences that relate indirectly to the calculated kermas of interest.

**Table 4. Neutron Kerma in Tissue Deduced from Cobalt Activation Measurements.**

| City | Coordinates of iron samples | Distance from hypocenter (m) | Incident angle | Activity (cpm/mg Co) | $Q_\theta$ (rate) | $N_\theta$ (R per cpm/ mg Co | Neutron dose (rad) |
|---|---|---|---|---|---|---|---|
| Hiroshima | 27.61 x 23.47 | 260 | 66.60 | 2.09 ±0.170 | 0.463 | 630 | 7865 |
| | 27.54 x 23.81 | 640 | 44.54 | 0.324 ±0.0204 | 0.485 | 586 | 1188 |
| | 27.30 x 23.89 | 779 | 41.69 | 0.146 ±0.0013 | 0.495 | 580 | 541 |
| | 27.50 x 46.12 | 1180 | 27.65 | 0.0124 ±0.0023 | 0.566 | 562 | 51 |
| Nagasaki | 51.29 x 46.02 | 590 | 42.55 | 0.140 ±0.0066 | 0.480 | 593 | 514 |
| | 50.42 x 46.49 | 1030 | 31.79 | 0.0127 ±0.0010 | 0.535 | 568 | 52 |

The incident angle is the angle between the wall of the building and a line to the hypocenter; $Q_\theta$ is the fraction of the $^{60}Co$ activity that is due to fast neutrons; $N_\theta$ is a measure of the dose rate per cpm per mg of cobalt. The dose was called "air dose" by Hashizume;[6] due to changes in nomenclature since 1967, it is now called the kerma-in-tissue at a point in air (see Editor's Note).

### Cobalt Activation

**Introduction and Comparisons.** The most extensively studied cobalt activation data were taken by Hashizume et al[6] using material from steel concrete reinforcing bars (rebars). These data were converted to kerma in tissue by an experimental calibration (Table 4). The lack of an appropriate neutron source for the calibration, however, makes the validity of the resulting kerma values subject to doubt. It is worth noting that a proper calibration source would be one whose spectrum reflects extended neutron transport through air. The transported spectrum has a shape largely independent of the emitted spectrum; so the peculiarities of the source actually creating the neutrons (as a bomb, or reactor) are not important, to a good approximation, for relating cobalt activation to kerma. Table 5 lists several determinations of the kerma per unit activity for $^{60}Co$. The first two entries in the table are related to the calibration made by Hashizume et al[6] and are high because of the absence of slow neutrons.[7] The other entries show the approximate independence from the type of source expected for extended transport.

Loewe[8] made a sequence of increasingly more accurate calculations of the cobalt activity, compared them with the measured data of Table 4, and demonstrated a growing divergence between them as the range increases (Figure 3). The remainder of this section traces that

Table 5. Estimates of the Quotient of Dose by Activity for $^{60}Co$.

| Impinging Spectrum | $M$ [rad/(cpm/mg)] |
|---|---|
| Hiroshima at 1180 m (Hashizume et al constructed) | 318 |
| HPRR at 1 m (calculated) | 280 |
| Hiroshima at 1180 m (calculated) | 70 |
| Hiroshima at 1180 m | |
| Little Boy | 70 |
| HPRR | 100 |
| Fat Man | 110 |

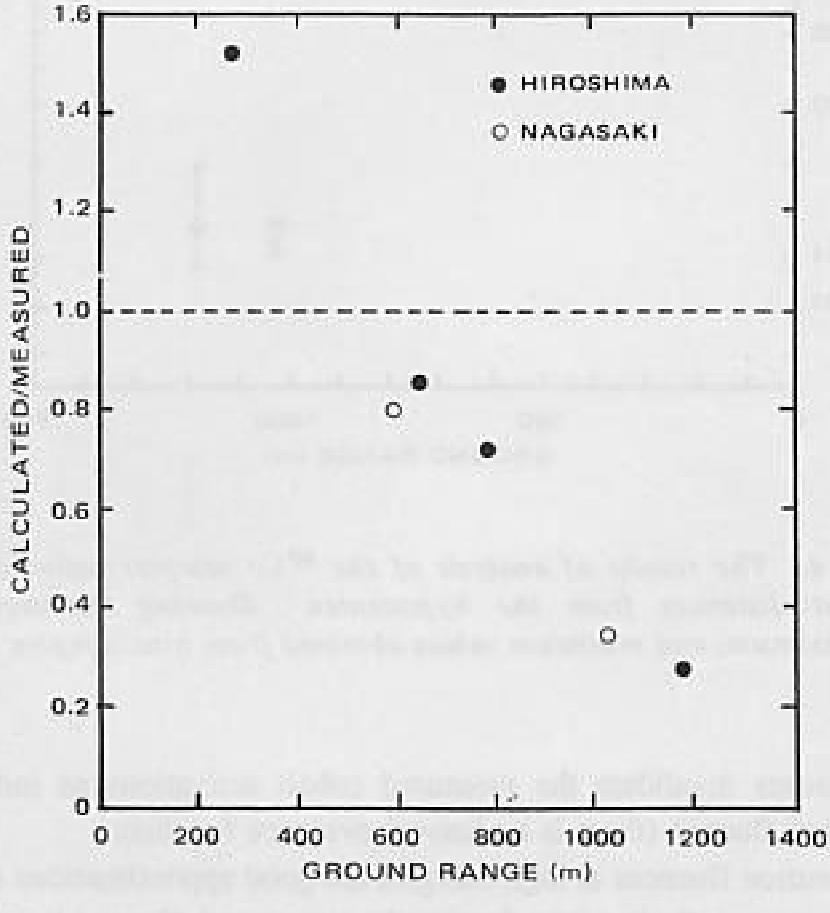



*Figure 3. Comparison of measured and calculated $^{60}Co$ activities.*

sequence and subsequent confirmative calculations and experiments. It is important to emphasize that the established experimental reproducibility of the initial data, as shown in Figure 4 taken from Kawamura et al,[9] is quite good compared to the discrepancies between calculated and measured values shown in Figure 3. The tops and bottoms of the bars in Figure 4 show the maximum and minimum values of a number of replicate determinations for each point. To indicate the significance to be attached to these discrepancies, a list of possible explanations for them is:

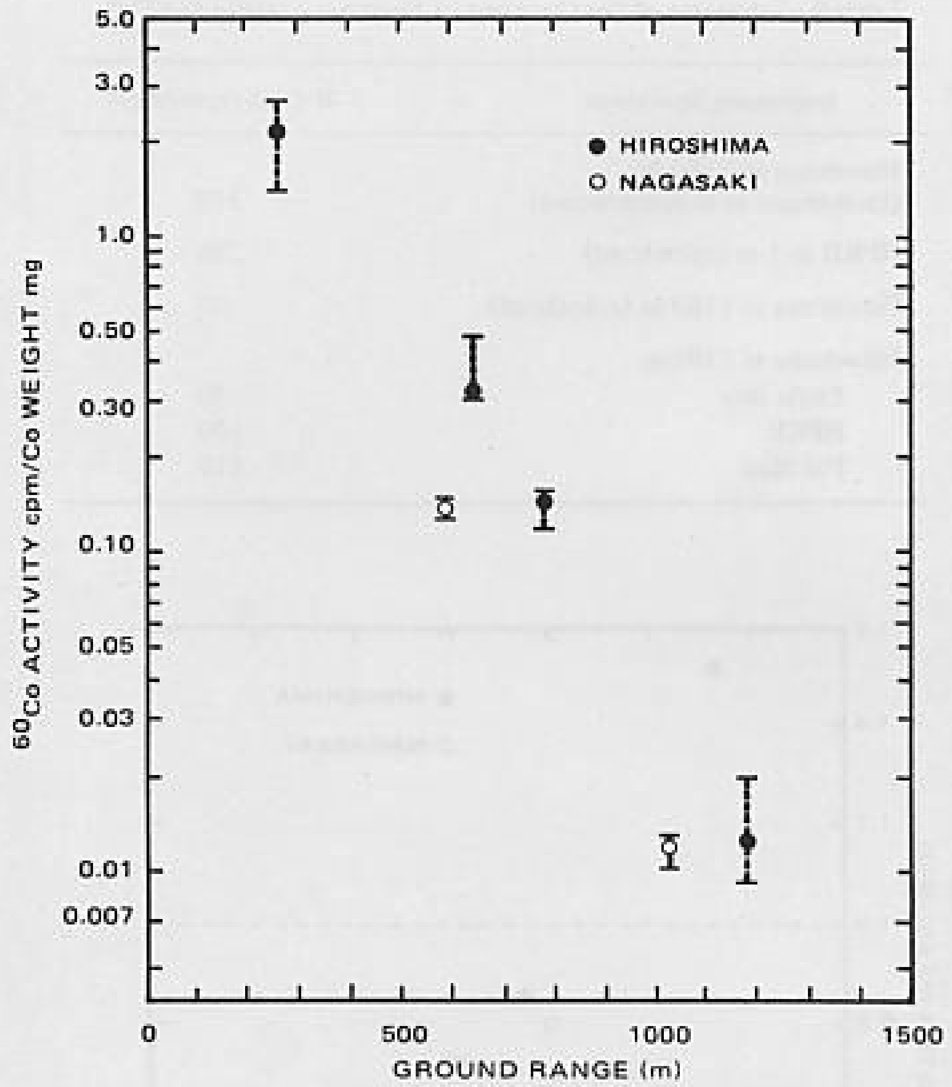



*Figure 4. The results of analysis of the $^{60}Co$ samples collected at different distances from the hypocenter. Showing the average, maximum, and minimum values obtained from nine samples.*

1. Unknown causes invalidate the measured cobalt activations as indicators of low-energy neutron fluence (there is no known evidence for this).
2. Calculated neutron fluences at high energies are good approximations to reality, but at low energies are greatly in error, despite the strong and obvious links between high- and low-energy neutrons (there is no known evidence for this).
3. Calculated neutron kermas at distances of greatest interest are in error by factors of three and greater (all other evidence contradicts this).
4. Some combination of errors in calculation and measurement is at fault (e.g., a harder than calculated neutron spectrum at Hiroshima plus an error in measurement of one of the points at Nagasaki could explain the discrepancies).

The first reported calculations of cobalt activation for comparison to measured values were based on a one-dimensional representation of the actual air-over-ground configuration and on an assumed composition for the concrete in which the rebars containing the cobalt were embedded.[7] At the measured point at Hiroshima at greatest ground range, the calculated result exceeded that measured by a factor of 1.5. A rough estimate of two-dimensional effects, based on proportionalities with calculated kermas, brought this factor down to 1.1. The calculated values were shown to be insensitive to the composition of the concrete except for the boron.

Improvements on this original estimate were made as follows. A factor of 0.67 resulted from changing to an improved source description for the Hiroshima bomb.[10] A factor of 0.59 resulted from changing to a composition for the concrete that contained boron, obtained from a typical building in Nagasaki by Maruyama (Appendix 5-3). A factor of 0.45 (instead of the roughly-estimated 0.73 in Loewe and Mendelsohn[7]) resulted from using a two-dimensional model of the concrete pillar (Loewe[3]) where the calculated two-dimensional activities shown in Figure 8 of that report contain a computer error that was corrected soon after the workshop at which the report was presented. These factors reduce the value of $8.1 \times 10^6$ atoms of $^{60}$Co per milligram of exposed $^{59}$Co reported by Loewe and Mendelsohn[7] to $8.1 \times 10^6 \times 0.67 \times 0.59 \times 0.45 = 1.4 \times 10^6$ (Table 6). An increment of $0.1 \times 10^6$ is due to delayed neutrons, the subject of the Loewe report.[8] Table 6 gives the calculated values, for both prompt and delayed neutrons, of the activity per unit mass of cobalt. The measured value at the farthest distance at Hiroshima was $5.31 \times 10^6$, giving the ratio ($1.5 \times 10^6 \div 5.31 \times 10^6 = 0.28$) shown in Figure 3 as part of the current status of the comparison between calculated and measured values.

**Table 6. Calculated Cobalt Activities.**

| | Distance from Hypocenter (m) | Millions of Atoms of $^{60}$Co per mg of $^{59}$Co | | | |
|---|---|---|---|---|---|
| | | Delayed | Prompt | Total | Delayed/Total ($\sigma_0$) |
| Hiroshima | 260 | 50 | 1300 | 1350 | 3.7 |
| | 640 | 6.5 | 110 | 117 | 5.6 |
| | 779 | 2.4 | 43 | 45 | 5.3 |
| | 1180 | 0.07 | 1.4 | 1.5 | 4.7 |
| Nagasaki | 590 | 28 | 20 | 48 | 58 |
| | 1030 | 0.77 | 1.15 | 1.9 | 41 |

**Studies of Calculated Results.** A number of studies were made to assess the calculations of cobalt activation. Loewe[3] showed that use of the three-dimensional Monte Carlo transport model, used in the sulfur activation estimates described above, confirms the two-dimensional results[8] as +20 to −10%, depending on the ground range. Details of the transport through concrete were also studied,[3] and Figure 5 (from that study) shows the effect the concentration of boron in the concrete has on activation of the rebars. Figure 6 shows that the calculated results are not sensitive to the low-energy approximations employed in the calculational models used nor to the exact depth of the rebars in the concrete pillar. Figure 7 shows the effect of removing from the calculation those neutrons that were already at thermal energy

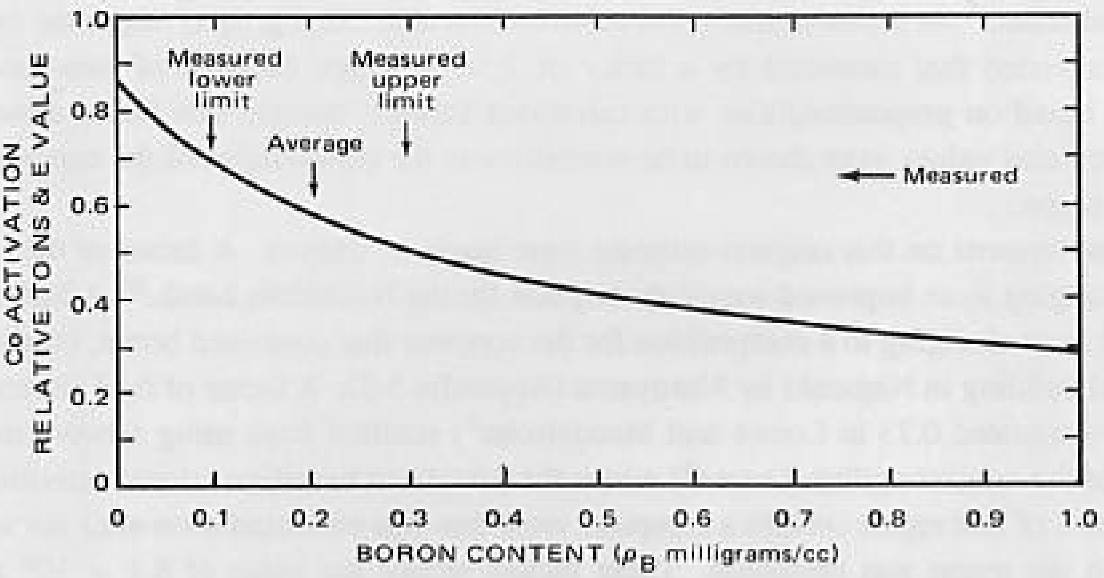



*Figure 5. The dependence of cobalt activation at Hiroshima on the boron content of concrete.*

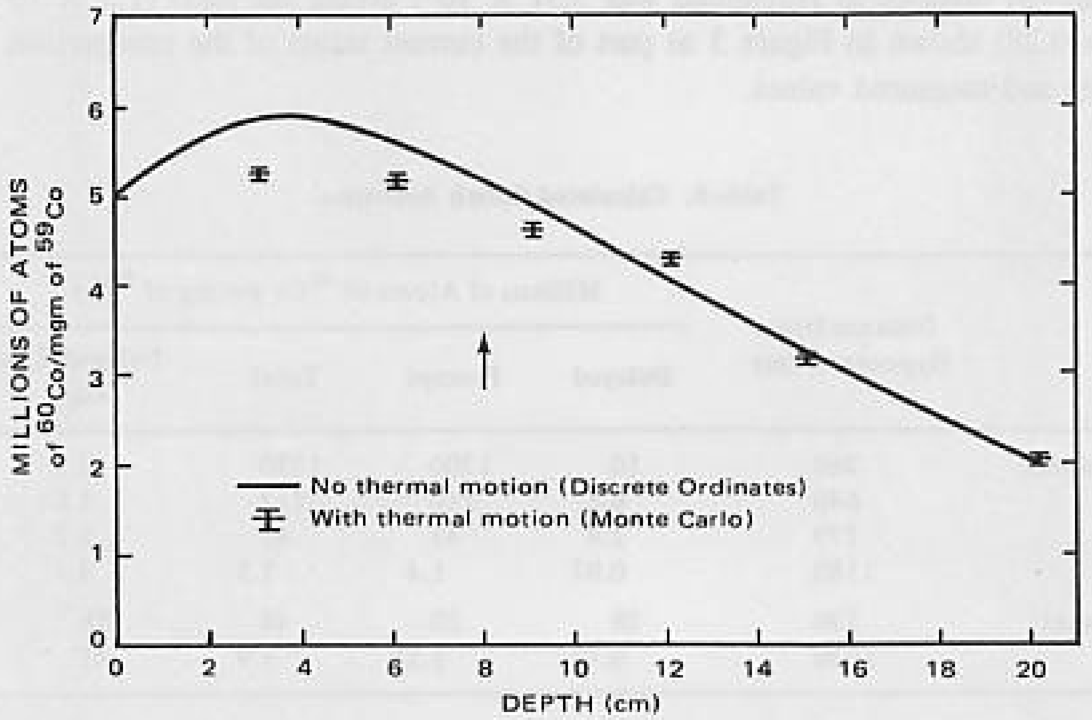



*Figure 6. $^{60}$Co activation versus depth in concrete at 1180 m at Hiroshima by two different methods.*

at the pillar face. At the depth in the concrete of the rebars, the activation is reduced only 8%. The rest of the activation is due to neutrons that had higher energies at the pillar face and lost energy untill thermalized in the transport to the depth of the rebars.

Using slowing down lengths for neutrons in water and scaled by hydrogen content to concrete, Loewe found that neutrons of one kilovolt or higher energies at the pillar face made negligible contribution to the activation. Most of the activation is due to impinging neutrons

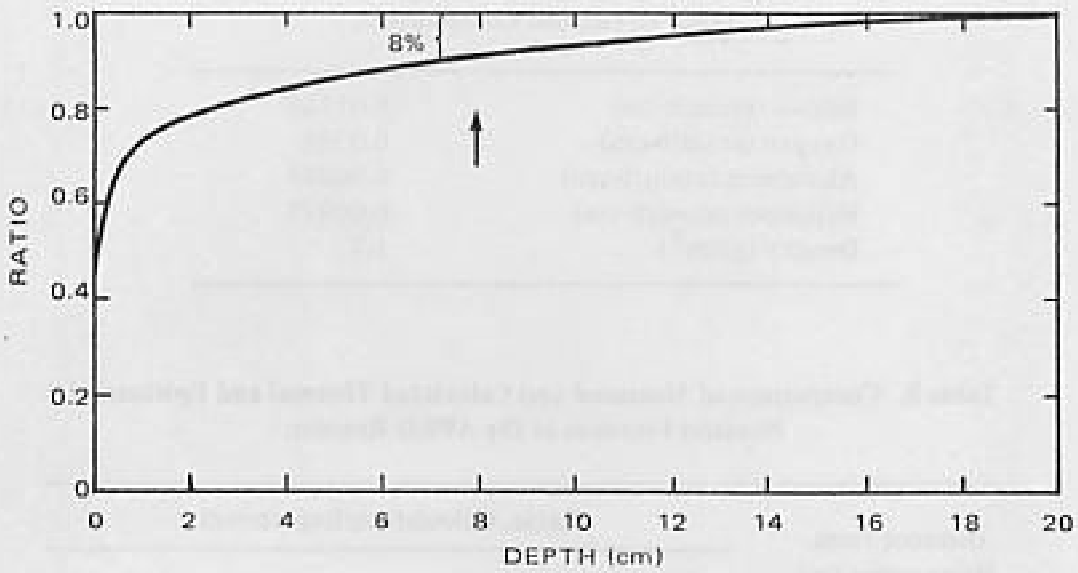



*Figure 7. The effect on cobalt activation of removing the thermal neutrons from the field at the face of the pillar.*

with energies one or more orders of magnitude lower (epithermal neutrons), depending on the moisture content of the concrete. Kaul generally confirmed this estimate of the energies of the neutrons that were effective in the activation of cobalt using calculations with truncated spectra incident on the pillar face.

Loewe, using estimates of blast wave velocities and neutron slowing down times, finds that hydrodynamic rearrangement of the atmosphere by the bomb blast should not affect the calculations of cobalt activation. Neutrons from the source reach thermal energies at 1000 m in less than about 0.5 second and thereafter survive only an additional 10% in time before being absorbed. The changes in the atmosphere arrive after one or more seconds, too late to affect the motion of the neutrons. Kaul confirmed these conclusions independently.

Table 7 gives the composition of the ground used in the cobalt activation calculations. This composition differs from that used in Chapter 3, but Loewe varied the constituents to show that no credible change in composition would have a major effect on the activation calculations. For example, if the relatively dry ground represented in the table is replaced by ground completely saturated with water (no air spaces left) the cobalt activation decreased by only 15%.

The calculated values used in Figure 3 were confirmed independently by Dolatshahi et al (Appendix 3-5). They agree to ± 3% with the Nagasaki calculations and fall 20 to 35% lower (than the measured results) at Hiroshima. They also found good agreement in comparing calculations with thermal fluences measured with subcadmium gold activation at nuclear weapons tests.

They also studied thermal and epithermal neutron fluences at the APRD reactor. Their results (Table 8) show excellent agreement between calculation and measurement. Loewe found a similar degree of agreement in subcadmium fluences. This degree of agreement clearly denies a factor of three or more calculational error at 1000 m that is required to resolve the discrepancy shown in Figure 3.

These studies suggest that the calculations used in Figure 3 do not suffer from conceptual

Table 7. Ground Composition.

| | |
|---|---|
| Silicon (atom/b-cm) | 0.01160 |
| Oxygen (atom/b-cm) | 0.0348 |
| Aluminum (atom/b-cm) | 0.00488 |
| Hydrogen (atom/b-cm) | 0.00977 |
| Density ($g/cm^3$) | 1.7 |

Table 8. Comparison of Measured and Calculated Thermal and Epithermal Neutron Fluences at the APRD Reactor.

| Distance from Hypocenter (m) | Ratio, Calculation/Experiment | |
|---|---|---|
| | Subcadmium Fluence | Epithermal Fluence |
| 100 | .94 | .75 |
| 170 | 1.03 | .84 |
| 300 | 1.05 | 1.12 |
| 400 | 1.16 | 1.14 |
| 1080 | 1.40 | .94 |

Measured data from reactor 8.2 m above ground at Aberdeen Proving Grounds, Maryland, USA.

omissions in the physics modeled. Comparison of the work of different authors also justifies the conclusion that the calculations do not contain inadvertant mathematical errors. Unless the neutron output of the Hiroshima weapon (discussed in Chapter 2) can be challenged at the factor-of-three level, the calculations appear to give sturdy and reliable estimates of cobalt activation. The measured values, which also appear to be robust, are discussed below.

**Studies of Experimental Results.** Hashizume et al[11] also reported measurements of cobalt activation obtained from samples of iron rings located on rooftops. The results were in close agreement with the embedded rebar data over the nearly 1000 m ground range where measurements were made. Loewe observed that the ratios of his calculated activations to the measured values were almost the same for rooftop sites as the corresponding ratios for embedded sites, if the assumed concrete compositions were reduced by a mere 19% in boron content. He had previously assumed, in generating Figure 3 and Table 6, that all sites in both cities had a concrete compostion that is the same as obtained by Maruyama (Appendix 5-3) for an unrelated but contemporary building at Nagasaki. Measurements of boron content made on samples taken from this building showed a variation of ± 50%. The 19% reduction in assumed boron content is very small compared to the uncertainty in the actual boron at the various sites. Table 9 compares these embedded and rooftop ratios of calculated to measured activations. This comparison suggests that the two separate sets of measurements form a larger, quantitatively consistent set that confirms the divergence of measured and calculated values shown in Figure 3 for the embedded data alone.

Thus the embedded samples at Hiroshima and Nagasaki and the bare samples at Hiroshima,

Table 9. Cobalt Activation at Hiroshima.

| Distance from Hypocenter (m) | Ratio, Calculated/Measured | |
|---|---|---|
| | Reinforcing Bar[a] | Rooftops |
| 260 | 1.20 | 1.15 |
| 640 | 0.67 | 0.62 |
| 1180 | 0.22 | 0.25 |

[a]Calculated data based on assumed boron content of concrete as 0.0002445 g/cc, compared to 0.0003 used by Loewe.[8]

over ground ranges covering about 1000 m from the hypocenter, constitute a measurement of the subkilovolt fluences that is not sensitive to concrete composition or thickness nor to sample location relative to either concrete or ground. Also, the variations from point to point are consistent with the measured statistical quality of about $\pm 35\%$ at 1180 m in Hiroshima. They show a high degree of internal consistencey that enhances their value.

Dr. Raymond Gold of the Hanford Engineering Development Laboratory noted that high-energy neutrons also generate $^{60}Co$ by the $(n, \alpha)$ reaction in $^{63}Cu$. Enough of these reactions would affect the amount of $^{60}Co$ measured. Their number would also decrease more slowly with distance, as do the fast neutron fluences and the measured cobalt activation, than do the calculated activations due to thermal neutrons. Loewe, however, estimated that the copper reaction could not produce a significant amount of $^{60}Co$. For his estimate he assumed high values for the cross section of the $^{63}Cu(n,\alpha)^{60}Co$ reaction: 0 to 3.7 MeV, 0.003 barns to 6.1 MeV, and 0.015 barns to 7.8 MeV. With fluences from the sulfur and cobalt calculations discussed above, he found a ratio of $1.5 \times 10^{-7}$ of $^{60}Co$ atoms formed per atom of $^{63}Cu$, to $^{60}Co$ atoms formed per atom of $^{59}Co$. Using representative compositions for iron in open-hearth ingots of about 70 ppm cobalt and 420 ppm copper and isotopic concentrations of 100% $^{59}Co$ and 69.2% $^{63}Cu$ gave an atom ratio in ingots of $^{63}Cu/^{59}Co$ of 4. Then the ratio of $^{60}Co$ atoms formed from copper in iron to $^{60}Co$ atoms formed from cobalt in iron is $1.5 \times 10^{-7} \times 4 = 6 \times 10^{-7}$. Even if cobalt were present at only 1 ppm in iron used for construction throughout prewar Hiroshima and Nagasaki and there was actually more copper than iron present, less than 10% of the measured $^{60}Co$ would be due to copper.

Another high-energy neutron reaction that transmutes an element in construction iron into $^{60}Co$ and with a cross section large enough to be significant was suggested by Dr. Gold's colleague, Dr. W. N. McElroy. He proposed the (n,p) reaction in nickel as a source of $^{60}Co$ atoms. Estimates similar to those just discussed for copper show that only a 45% increase in $^{60}Co$ would result, even for such extreme assumptions as (1) 20% nickel in iron rebars, (2) $\sigma(n,p)$ of $^{60}Ni$ as large as 0.4 barns, and (3) only 5 ppm cobalt in iron rebars. This 45% increase is to be compared with a factor of four needed to bring about agreement at 1180 m.

The cobalt measurements of Hashizume et al were recently reviewed carefully by two of the coauthors of the original paper, Dr. T. Maruyama and Dr. S. Kawamura. The results are given in Appendix 5-16 along with much additional detail on the sample locations to aid in more exact calculation modeling. They concluded there is no discernable difficulty with the experimental methods and the results should continue to be accepted as sound.

The new descriptions of the individual sample environments show significant differences from the idealized models used in the calculations. Scientists of Science Applications International Corporation agreed to repeat particular calculations using more accurate models based on the new information in the hope of coming nearer to agreement between the calculated and measured cobalt activations. In the meantime, however, the people who make the calculations are of the opinion that agreement will not be achieved because the drastic-appearing model changes are insufficient to produce large changes in the activation calculations.

Other measurements of $^{60}$Co were reported by Saito (Appendix 5-4) and by Hoshi and Kato (Appendix 5-5). Their measurements have not been subject to the same degree of scrutiny as the Hashizume data, in part because they do not extend to distances where most of the survivors were.

All of the cobalt measurements need additional study and intercomparison to see if they confirm the discrepancy with calculation shown in Figure 3. For example, the data of Hoshi and Kato are close enough to those of Hashizume et al that perhaps corrections for sample height and for any shadowing structures (e.g., the girders on the Aioi bridge) would improve the agreement. These studies are difficult. Each individual datum has peculiarities of its own that require careful expression as an uncertainty (or error) to be placed on the accuracy of the result. Such an error may be much larger than that associated with reproducibility alone.

The central issue remains as to whether the absolute uncertainties assigned to the experimental $^{60}$Co results are, in fact, sufficiently small to permit declaring the $^{60}$Co calculations to be clearly erroneous. Such a clear-cut declaration would then require a high degree of dissociation between the dose and the thermal fluence to save the present dose calculations from suspicion. At present no evidence for such a dissociation has been recognized; on the contrary, they are believed to be linked.

**Europium Activation**

A number of measurements have been made of the $^{152}$Eu induced in natural europium in rocks and structures by thermal or near-thermal neutrons (the cross section is nearly 1/v, inversely proportional to the velocity of the neutrons, from thermal to fission energies). The measurements by Nakanishi et al[12] on granite and rock samples are compared in Figure 8 with a curve calculated by Loewe, who folded the europium activation cross section with fluences obtained by the same procedures and with the same parameter values as used in the kerma, sulfur activation, and cobalt activation calculations.

Also shown in the figure are more recent data obtained by Sakanoue et al (Appendix 5-7), Nakanishi (Appendix 5-14), and Okajima and Miyajima (Appendix 5-6). Data by Hoshi and Kato (Appendix 5-5) taken near 300 m from the hypocenter at Hiroshima also agree well with the data in Figure 8.

At the present stage of development, all of the measured values, taken collectively, form a body of experimental data which show no discrepancies in comparison to calculated results. The values have sufficient uncertainty, however, to prevent confirmation of calculations at 1000 m at a confidence level high enough to bear on the cobalt discrepancy discussed previously.

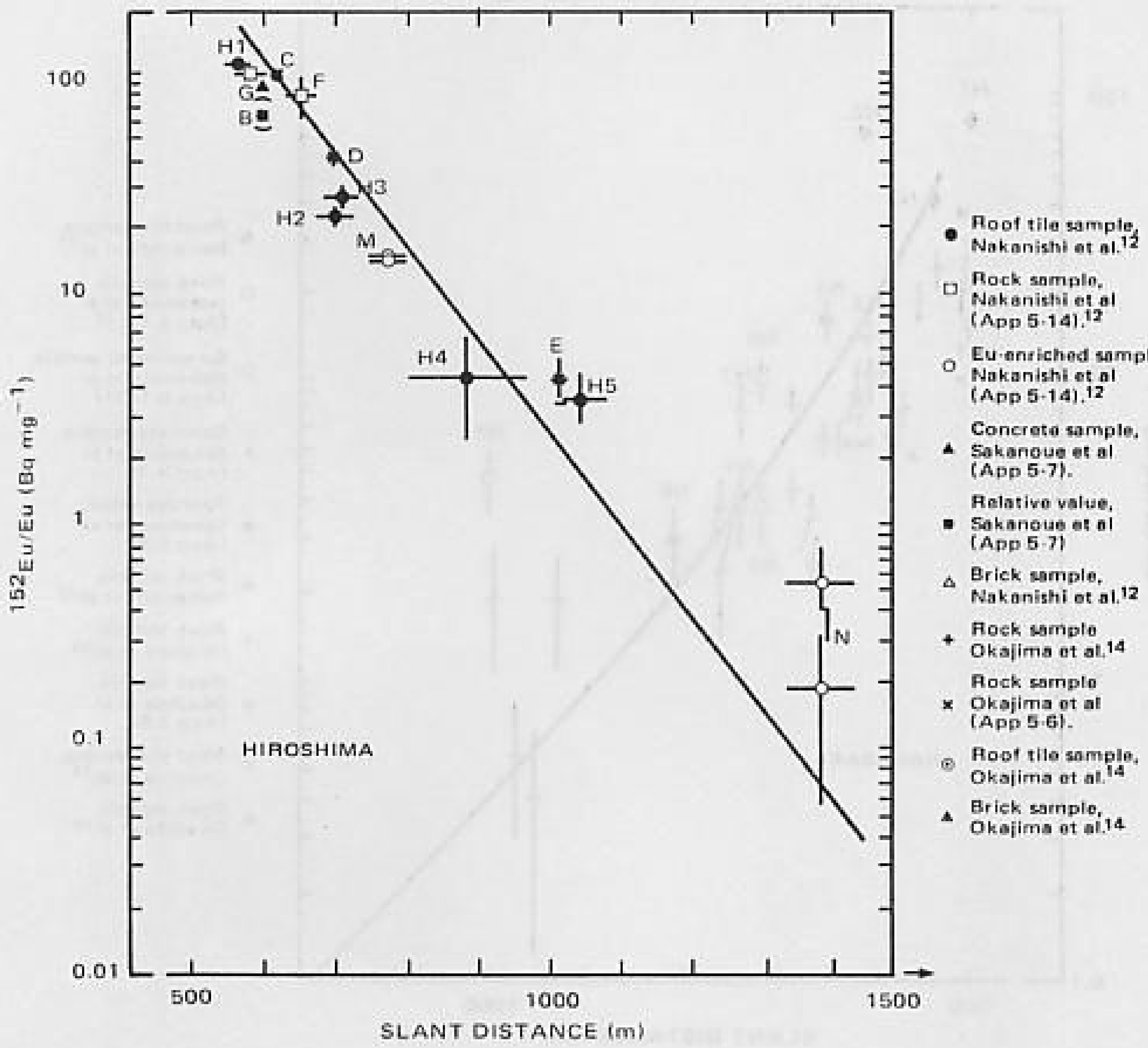



*Figure 8(a). Comparison of measured and calculated $^{152}Eu$ activity immediately after the nuclear explosion, Hiroshima.*

However, these results are highly suggestive and may be susceptible to additional work to tighten the spread in data, especially at Nagasaki. Two possibilities have presented themselves. First, rock samples show more variable results, due to ground water variations, than do samples taken at elevated locations; so they should be accorded lesser weight. Second, different laboratories show consistent differences in results that could be diminished by an interlaboratory exchange of samples for calibration as was done with the thermoluminescence data discussed in Chapter 4. If these possibilities can be more fully developed experimentally, the uncertainties in the experimental data might be reduced to the point where confirmation or denial of the calculated results could be made with a sufficiently high level of confidence that the cobalt discrepancy could be resolved.

## Gold Activation

No data on the activation of gold in Hiroshima or Nagasaki were obtained, but mea-

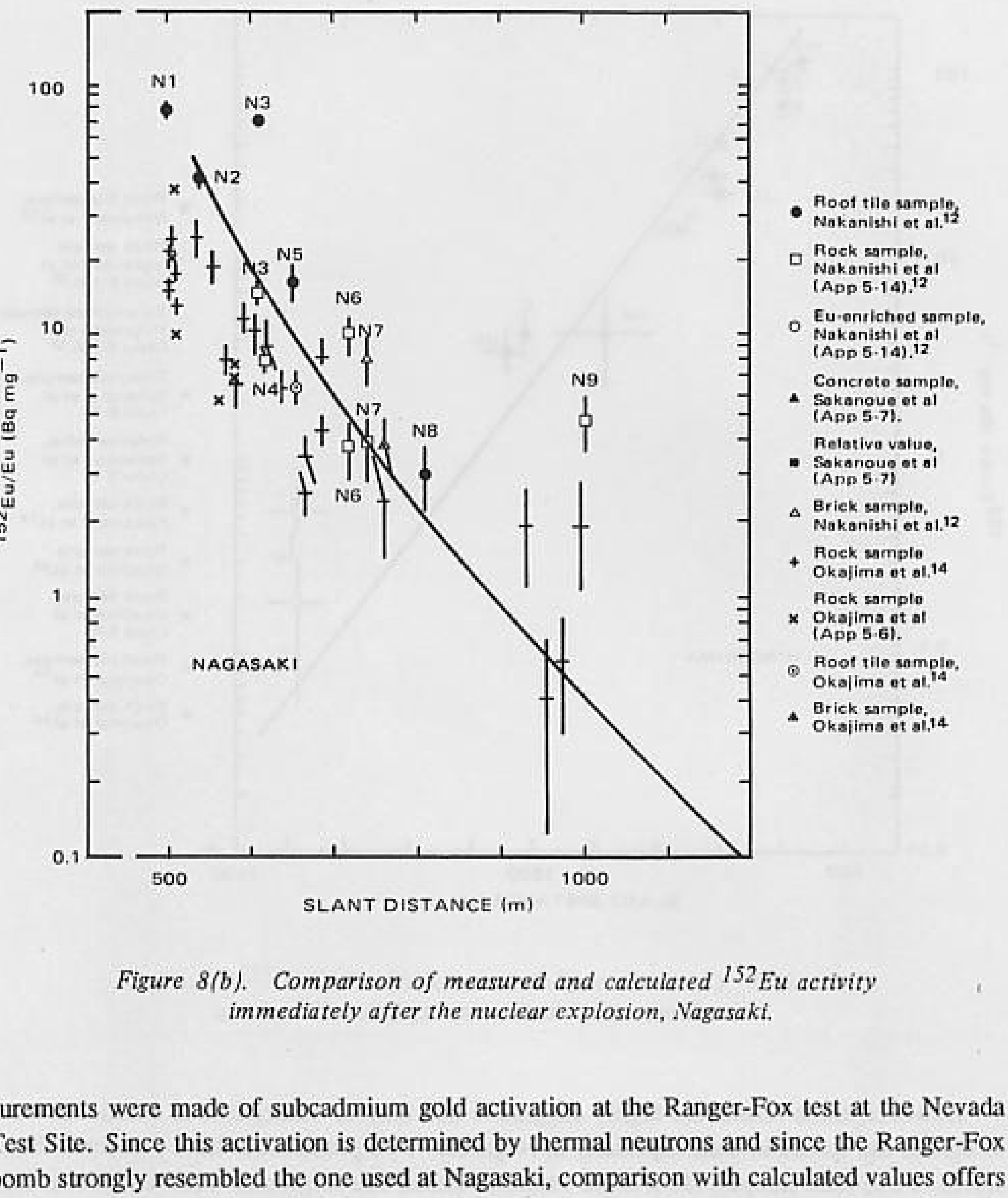



*Figure 8(b). Comparison of measured and calculated $^{152}Eu$ activity immediately after the nuclear explosion, Nagasaki.*

surements were made of subcadmium gold activation at the Ranger-Fox test at the Nevada Test Site. Since this activation is determined by thermal neutrons and since the Ranger-Fox bomb strongly resembled the one used at Nagasaki, comparison with calculated values offers an important test of the calculation procedures. It does not test parameter values unique to Hiroshima or Nagasaki, such as atmospheric conditions, ground cover, etc. Dolatshahi et al (Appendix 3-5) made these comparisons (Figure 9). Loewe confirmed these results using the same procedures he used in preparing Table 3. The figure shows agreement to better than a factor of three at all ranges and shows improvement, as range increases, becoming about 20%. In all cases, except the most distant point (near 1600 m), the calculated values of thermal fluences are larger than the measured values. This is opposite to the cobalt case, where calculated values fall progressively lower beyond 500 m ground range. A similar comparison was made for the Buster-Jangle Dog test, where the bomb was also similar to the one used at Nagasaki (Appendix 3-5).

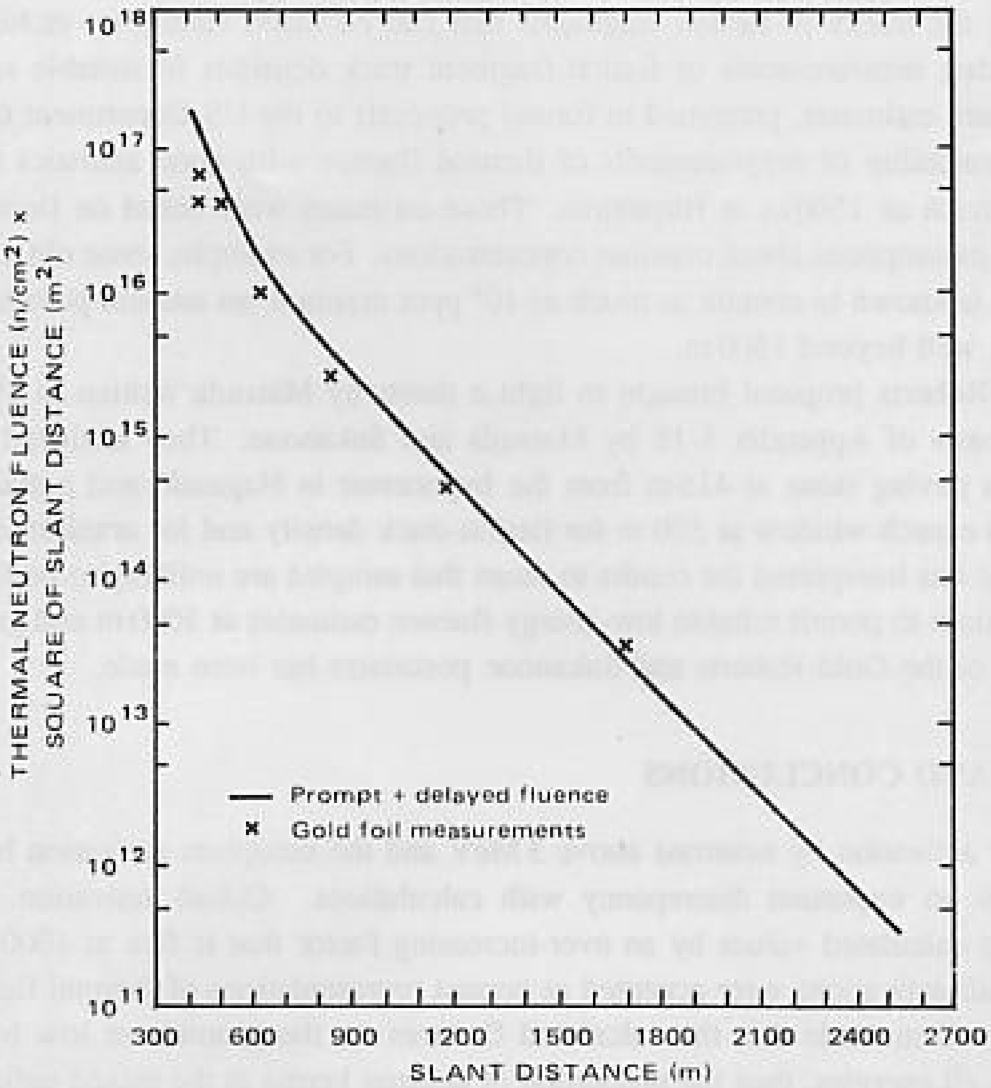



*Figure 9. Comparison of thermal neutron fluences measured with gold foils at Shot Ranger-Fox with calculations.*

The results with gold activation lead to the conclusion that no important physical mechanisms were omitted and no important errors in neutron cross-section values or source description were made in calculating the thermal fluences at Ranger-Fox, an experimental surrogate for Nagasaki. They serve, therefore, as additional evidence supporting the calculated thermal fluences at Hiroshima and Nagasaki. However, the difference between the rates at which the measured and calculated Ranger-Fox data decrease with range seen in Figure 9 tends to mitigate the authority of the data as support for the calculated thermal fluences. Acceptance of the calculated thermal fluences would lead to the hypothesis that the measured cobalt activations at Hiroshima and Nagasaki do not accurately reflect the thermal neutron fluences. The hypothesis could be justified by discovering some channel for creating significant amounts of $^{60}Co$.

**Uranium Activation**

Gold and Roberts[1] pointed out that a permanent record of uranium fissions exists in a variety of materials, such as zircons and man-made glassware, in the form of radiation damage along the tracks of fission fragments that can be made visible by etching. They proposed making measurements of fission-fragment track densities in suitable specimens. Their subsequent estimates, presented in formal proposals to the US Department of Energy, suggest the possibility of measurements of thermal fluence with good statistics to ground ranges of as much as 1500 m at Hiroshima. These estimates were based on fluences from Loewe[13] plus assumptions about uranium concentrations. For example, some old, man-made glass in Japan is known to contain as much as $10^4$ ppm uranium, an amount permitting good measurements well beyond 1500 m.

The Gold-Roberts proposal brought to light a thesis by Matsuda written in 1977. This thesis is the basis of Appendix 5-15 by Matsuda and Sakanoue. They analyzed a granite sample from a paving stone at 415 m from the hypocenter in Nagasaki and a stained glass sample from a church window at 520 m for fission-track density and for uranium concentration. Sakanoue has interpreted the results to mean that samples are unlikely to be found with sufficient uranium to permit reliable low-energy fluence estimates at 1000 m and greater. No reconciliation of the Gold-Roberts and Sakanoue postulates has been made.

## SUMMARY AND CONCLUSIONS

The sulfur activation by neutrons above 3 MeV and the europium activation by thermal neutrons show no important discrepancy with calculations. Cobalt activation, however, contradicts the calculated values by an ever-increasing factor that is five at 1000 m. If the measured cobalt activations were accepted as correct representations of thermal fluences and the assumption then made that the calculated fluences on the ground are low by a factor that applies to all energies, then the proportion of neutron kerma in the mixed radiation field beyond 1000 m at Hiroshima would change from insignificant to significant.

The sulfur activation is due to neutrons that are close in energy to those that produce most of the neutron dose. The excellent agreement with calculation close to the hypocenter, however, deteriorates at 1000 m to such a degree that experimental support is weak for the calculated kerma at 1000 m and more. The europium activation is sufficiently uncertain at all ranges, but especially so at large ranges, that its support for the calculated low-energy fluences is weak. In contrast, the cobalt determinations made by the Hashizume group show small variability, good consistency, and good reproducibility for data as far as 1000 m from the hypocenter.

Strong efforts to resolve the cobalt discrepancy from both the calculation and experimental sides have only served to confirm its existence.

Because the calculations have been quite thoroughly "scrubbed" and are generally based on data and procedures admitting of limited error, we believe there must be some unrecognized contribution to the measured $^{60}$Co activity that has not been included in the calculation model. However, until such a contribution is identified, it is necessary to assume that it does not exist.

If it does not, it is possible that erroneous calculated fluences are only weakly related to high-energy neutrons that determine dose. There is presently no evidence for this supposition, and, in fact, those most experienced in calculational development of thermal neutrons from fast neutrons are most skeptical. It is important to recognize that neutrons that produce the kerma at one distance from the epicenter have the same energies as other neutrons that activate cobalt some hundreds of meters farther away. The transformation of the latter into thermal neutrons results exclusively from interaction with common materials (nitrogen, oxygen, silicon) that have scattering cross sections that are well known at all relevant energies and produce energy losses by known laws of classic mechanics. There is only a very limited opportunity for error in the modeling.

This leaves the possibility, however unlikely in our collective expert judgment, that the calculated neutron kerma values are wrong. No known evidence contradicts this hypothesis. Therefore, the conclusion of this chapter on neutron measurements must be that the neutron doses are in doubt until further work is done. Special value would attach to additional work on measurement of thermal neutron fluences based on unmistakable physical effects occurring in sufficiently great strength as to permit good quality results beyond 1000 m from the hypocenter. One suggested candidate is fission-track density in uranium-bearing glassware or materials containing zircon fragments, but no high-uranium containing specimens have been found.

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