Other Cobalt Activation Studies

Finally, data on cobalt activation at Hiroshima and Nagasaki from three additional studies are summarized in Table 11. The three studies are those by Saito (1961), Hoshi and Kato (1987), and Nakanishi et al. (1987). The 1961 study by Saito demonstrated the possibility of investigating the neutron fluences from the atomic bomb explosions at Hiroshima and Nagasaki using the induced activity in steel samples that contain cobalt as an impurity. The 1987 study by Hoshi and Kato provides data from measurements of the induced ^{60}Co activity in various materials from three sites at Hiroshima: (1) iron materials from the Sumitomo Bank Building; (2) iron and granite materials from the Fukoku Life Insurance Building; and (3) iron and granite materials from the Aioi Bridge (or so-called T-Bridge). Only the measurements from the first two sites are included in Table 11, because the samples from the T-Bridge were shielded partially by the deck of the bridge and effect of this shielding on the induced ^{60}Co activity in the samples has never been fully evaluated. The 1987 study by Nakanishi et al. provides data on the induced ^{60}Co activity in a roof tile from the Shima Hospital and a granite sample from the Motoyasu Bridge. More information on these studies can be found in the above references and Shizuma et al. (1992).

Table 11. Summary of data on cobalt activation from other studies (Saito 1961; Hoshi and Kato 1987; Nakanishi et al. 1991)

City and sample location	Material[a]	Ground range (m)	Initial activity (Bq/mg of Co)	Reference
Hiroshima				
Shima Hospital	Roof tile	15	12.50 ± 0.99	b
Motoyasu Bridge	Granite	128	12.8 ± 5.1	b
A-bomb Dome	Guttering	150	4.05 ± 0.06	c
	Guttering	150	3.96 ± 0.28	c
Sumitomo Bank	Iron ring	262	6.0 ± 1.3	d
Fukoku Life Insurance Co.	Iron ring	322	5.7 ± 0.6	d
	Iron ring	322	6.7 ± 0.6	d
	Iron ring	344	5.9 ± 0.6	d
	Iron ring	344	6.8 ± 0.6	d
Nagasaki				
Nagasaki Medical College	Iron rod	523	0.337 ± 0.138	c
	Iron rod	523	0.432 ± 0.138	c

[a]Sample from Motoyasu Bridge was from a granite bridge pillar and all other samples were from the roofs of the buildings.

[b]See Nakanishi et al. (1987, 1991) and Shizuma et al. (1992).

[c]See Table 1 of Saito (1961) and Table 5 of Shizuma et al. (1992). Table 1 of Saito (1967) gives the activity in disintegrations per second per gram of Co at the time of measurement in September 1960. The initial activity in Bq per mg of Co at the time of bombing in August 1945 is obtaining by multiplying these values 7.29 $\times 10^{-3}$.

[d]See Hoshi and Kato (1987) and Shizuma et al. (1992). Only one of the four measured values of Hoshi and Kato for the Fukuko Like Insurance Company is listed in Table 5 of the 1992 report by Shizuma et al.

Cobalt-60 Background from Environmental Neutrons

An extremely difficult problem to address experimentally has been the saturated ^{60}Co activity in steel due to cosmic-ray neutrons and other environmentally produced neutrons. Calculations indicate that the thermal neutron flux near the surface of the earth is approximately 1.5×10^{-3} n cm^{-2} s^{-1} (O'Brien et al. 1978), and the saturated background activation from environmental neutrons was calculated to be approximately 6×10^{-7} Bq per mg of Co (Kerr et al. 1990). As discussed in the previous section of this report, Kerr et al. counted two radically different samples to establish the background count rates for their ^{60}Co measurements at PNL. One of the steel samples was obtained from a deep underground mine in South Dakota, and the other from a light steel-frame building in Tennessee. The latter steel sample had been exposed to cosmic-ray neutrons, and the former sample was not. The expected difference in the count rates based on calculation for the above ground sample was 0.0003 cpm, and the measured difference between the two different plates was 0.0002 cpm (Kerr et al. 1990). It was determined from these measurements that the saturated ^{60}Co activity from environmental neutrons did not contribute significantly to the ^{60}Co activity from bomb-produced neutrons at ground ranges of 1,300 m or less at Hiroshima. Komura (2001b) has also made experimental measurements of the ^{60}Co activity induced in chemical reagents by environmental neutrons (Table 12). His measured value was about 1 mBq per g of Co (1×10^{-6} Bq per mg of Co) for the saturated activity in cobalt from environmental neutrons. This value is in good agreement with the saturated activity value of 6×10^{-7} Bq per mg of Co from Kerr et al. (1990), and it is now generally agreed that environmental neutrons do not contribute significantly to ^{60}Co measurements made at Hiroshima or Nagasaki (Shizuma et al. 1998, 2002; Komura 2001b).

Table 12. Induced ^{60}Co activity in reagents exposed to environmental neutrons at sea level for varying periods of time (Komura 2001b)

Sample	Age	Weight (g of Co)	Measurement date	Activity (mBq/g of Co)[a]	Remarks
Co-oxide	Old	17.4	06/26/1998	0.11 ± 0.04	Shielded
Co-nitrate	Old	3.78	08/11/1998	1.39 ± 0.27	Saturated
Co-oxide	Modern	35.5	08/29/1998	1.12 ± 0.09	Saturated
Co-metal	Modern	50.0	08/16/1998	0.92 ± 0.08	Saturated
Co-oxide	Modern	35.5	07/29/1999	0.08 ± 0.03	Unsaturated
Co-nitrate	Modern	7.34	12/04/2000	0.18 ± 0.18	Unsaturated

[a]One mBq/g of Co is equal to 1×10^{-6} Bq/mg of Co.

Transmission Factors for Cobalt Activation

The method of comparing measurements and calculations in the DS86 studies was to plot ratios of the measured values (M) and calculated values (C) as a function of slant range (Figures 3 and 4). This approach had a tendency to draw attention away from the problems causing the DS86 neutron discrepancy at Hiroshima. A more direct approach is used here for comparing calculated and measured values based on the following equality:

$$\frac{A_{meas}(R,h)}{A_{meas}(R,1m)} = \frac{A_{calc}(R,h)}{A_{calc}(R,1m)} \quad . \qquad (1)$$

This equation assumes that one would obtain the same ratios from (a) a set of activation measurements, $A_{meas}(R,h)$, in a shielded or unshielded sample at a height, h, above ground and, $A_{meas}(R,1m)$, in a small unshielded sample exposed free-in-air (FIA) at 1 m above ground at the same ground range, R, and (b) a set of activation calculations, $A_{calc}(R,h)$, for the shielded or unshielded sample at the same height, h, above ground and, $A_{calc}(R,1m)$, for the small unshielded sample exposed FIA at 1 m above ground at the same ground range, R, as the measurements. The above equation can be rewritten in several different ways. One way is to define a so-called transmission factor, TF, as follows:

$$TF = \frac{A_{calc}(R,h)}{A_{calc}(R,1m)} \quad , \qquad (2)$$

so that

$$A_{meas}(R,1m) = \frac{A_{meas}(R,h)}{TF} \quad . \qquad (3)$$

Thus, it is possible to use the calculated TFs as defined above and the measurements made in a shielded or unshielded sample on a structure at a height, h, above ground to obtain equivalent measurements in an unshielded sample exposed FIA at 1 m above the standard wet ground used in the air-transport calculations (Chapter 3). The TF calculations must model the local environments of the measured samples as precisely as possible for the comparisons to be reliable.

Transmission factors, TF, calculated for the rebar and iron ring samples used in the JNIRS studies (Hashizume et al. 1967; Hashizume 1983) and for the samples from the Chugoku Electric Company and Yokogawa Bridge used in the ORNL and JCAC studies (Kerr et al. 1990; Kimura et al. 1990; Kimura and Hamada 1993) are provided in Table 13. A schematic showing of the Sentry Box from a report on the JNIRS studies (Maruyama and Kawamura 1987) is shown in Figure 7, and the model used in the calculations for the rebar samples from the Sentry Box is shown in Chapter 8, Part J of this report. The TF for the Sentry Box in Table 13 (i.e., 0.86), and the results of the JNIRS ^{60}Co measurements for the rebar samples from the Sentry Box in Table 3 (i.e., 0.581 ± 0.0366 Bq/mg of Co) are used as follows to obtain an equivalent measurement in a small unshielded sample exposed FIA at the ground range of 684 m of the Sentry Box:

$A_{meas}(684\ m,1\ m) = (0.581 \pm 0.0366$ Bq/mg of Co$)/0.86 = 0.676 \pm 0.0426$ Bq/mg of Co.

The calculated value for a small unshielded sample of steel exposed FIA at a ground range of 684 m and a height of 1 m above wet ground is 0.557 Bq/mg of Co, and the measured-to-calculated ratio for this example is 1.21 ± 0.0076. The TFs have not been calculated for all samples used in the ^{60}Co measurements, but some general rules can be used to estimate TFs for these samples if one has some knowledge of the following parameters: (1) sample height; (2) shielding of the sample by surrounding materials; (3) shielding by other nearby structures; and (4) composition of the sample materials. At Hiroshima and Nagasaki, most of the ^{60}Co measurements were made in samples that were near the surface with no line-of-sight shielding in the direction toward the burst point of the bomb. For these samples, an approximate TF of 0.9 with a standard deviation of about ± 0.1 can be used (Chapter 8, Part J).

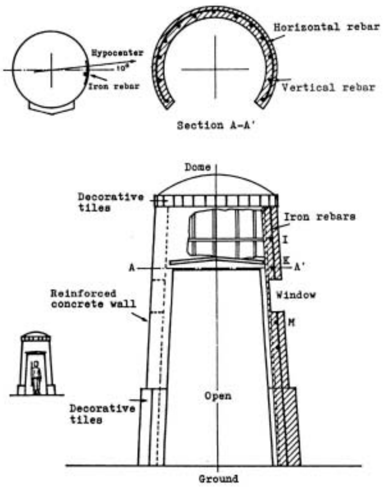

Figure 7. *Schematic of Sentry Box in the military area of Motomachi near Hiroshima Castle (Maruyama and Kawamura 1987). The horizontal rebars from the Sentry Box were used in the ^{60}Co activity measurements by the Japanese Institute of Radiological Sciences (Hashizume et al. 1967; Kawamura et al. 1967).*

Table 13. Transmission factors for specific iron and steel samples from Hiroshima

Sample and sample location	Transmission factors
Rebar samples[a]	
Hiroshima Bank	0.62
Sentry box	0.86
Water trough for horses	0.81
Powder magazine	0.71
Ring samples[a]	
Honkawa Elementary School	0.74
Fukuromachi Elementary School	0.78
Kirin Beer Hall	0.78
Kodokan Building	0.80
Hiroshima City Hall	0.76
Handrail sample from smokestack[b,c]	
Chugoku Electric Company	0.87
Yokogawa Bridge samples[b,c]	
Plate 3A	0.50
Plate 3B	0.40
Plate 4C	0.40
Plate 4D	0.52

[a]See Chapter 8, Part J of this report.
[b]Calculated from data in Kerr et al. (1990).
[c]More information on these samples and their locations can be found in Kerr et al. (1990), Kimura et al. (1990), and Kimura and Hamada (1993).

Comparisons with DS02 Calculations

Comparisons of DS02 with DS86 and with the ^{60}Co measurements in Tables 3 through 11 are shown in Figures 8 and 9. The DS02 calculations maintain the same 503-m burst height and 21-kt yield as used in the DS86 calculations for Nagasaki (Kerr et al. 1987). However, the DS86 values of 580 m for the burst height and 15 kt for the yield are not used in the DS02 calculations for Hiroshima. The new DS02 Hiroshima calculations for a burst height of 600 m and yield of 16 kt were found to provide the best possible overall agreement with all neutron-activation measurements, including ^{60}Co, and all TLD measurements for gamma rays (Chapter 1). The excellent agreement with the close-in measurements of ^{60}Co at Hiroshima is shown in Figure 10. At Hiroshima, there is good overall agreement between the DS02 calculations and ^{60}Co measurements out to ground ranges of about 1,300 m with one possible exception (Figure 8). It appears that there was a problem with either counter calibration or operation during the JNIRS measurements of ^{60}Co in the iron-ring samples. The results of the TF calculations for the iron-ring and steel-rebar samples suggest that the ^{60}Co activation in the two different kinds of samples should have been approximately the same (Table 13), but the ^{60}Co count rate data (cpm/mg of Co) and the estimated initial activity (Bq/mg of Co) are approximately two times greater in the iron rings than in the rebars (Tables 1 and 3). For example, the initial activities of the steel rebar from the Sentry Box at 684 m and iron ring from the Kirin Beer Hall at 693 m are 0.581 and 1.08 Bq/mg of Co, respectively (Table 3) and the raw count rates for these two samples are 0.324 and 0.548 cpm/mg of Co, respectively (Tables 1 and 3). The iron-ring measurements are based on only one measurement at each sample location, all of them performed in a single series of measurements between 29 September 1965 and 10 October 1965. The rebar measurements, on the other hand, were based on anywhere from 4 to 29 replicate measurements at each sample location, and most of the replicate measurements were done in such a way that earlier measurements were rechecked by later measurements in a different series, separated by several months in time. At ground range of more than 1,300 m at Hiroshima, there also appears to be a problem distinguishing between sample counts and detector background (Figure 11). The estimated initial activities in the distant samples depend to some extent on both the detector used in the measurements and the method of determining count rates for the 1173- and 1333-keV gamma rays from ^{60}Co (Tables 6 through 9).

The neutron calculations for the Nagasaki bomb have been, and continue to be, verified in a fundamentally different way than those for the Hiroshima bomb. Nagasaki type-bombs were detonated during a number of early weapon tests in New Mexico (Alamogordo), the south Pacific (Bikini Atoll), and the Nevada Test Site (NTS). The activation of gold by thermal neutrons and that of sulfur by fast neutrons at several of these tests have been calculated with the same calculational techniques used in the DS02 reassessment effort (Chapter 3). Small differences are observed between calculations and measurements for neutron activation at these NTS tests compared to the scattering observed between the ^{60}Co measurements and DS02 neutron calculations for Nagasaki. Nevertheless, all of the neutron activation measurements, including those for ^{60}Co, and all TLD measurements were systematically compared with the DS02 calculations, and the analysis produced an overall best result for a height of burst and bomb yield that were very close to the 503-m and 21-kt values used previously for the Nagasaki explosion (Chapter 1).

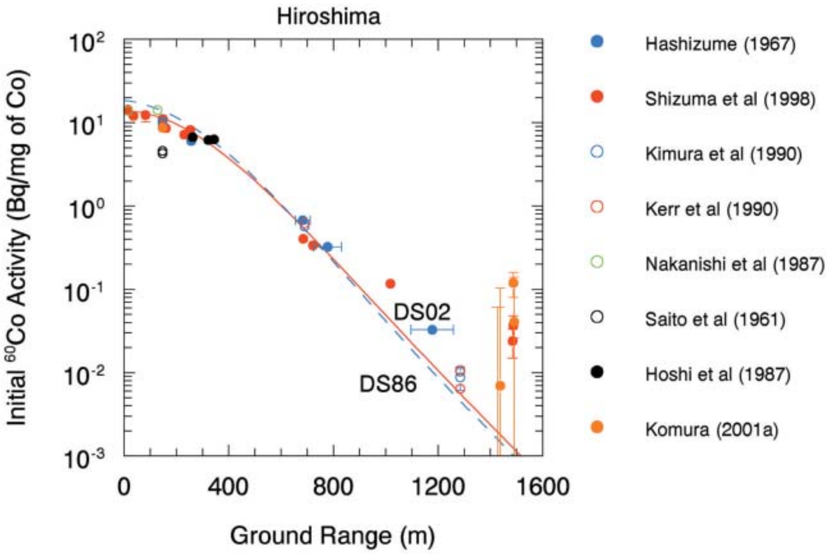

Figure 8. *Comparison of ^{60}Co measurements at Hiroshima with DS02 and DS86 calculations. The DS86 calculations assume a 580-m burst height and 15-kt yield at Hiroshima, and the DS02 calculations assume a 600-m burst height and 16-kt yield.*

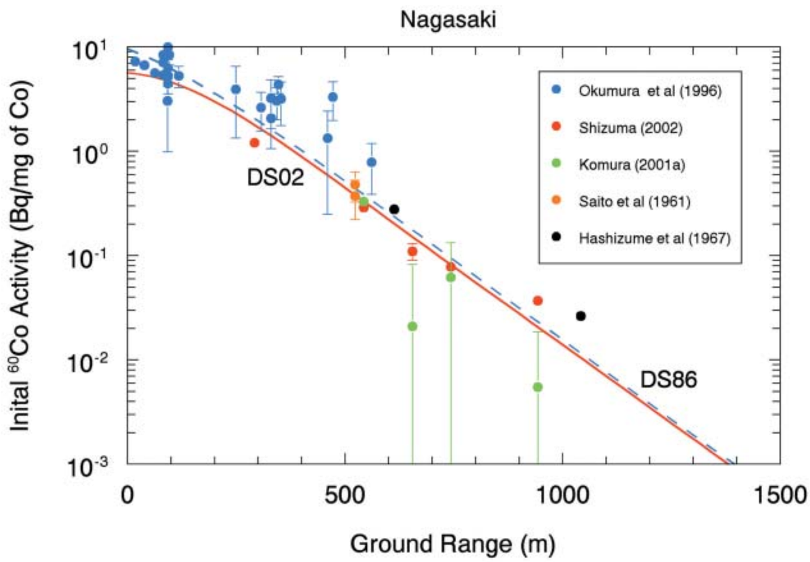

Figure 9. *Comparison of ^{60}Co measurements at Nagasaki with DS02 and DS86 calculations. Both the DS86 and DS02 calculations assume a 503-m burst height and 21-kt yield at Nagasaki.*

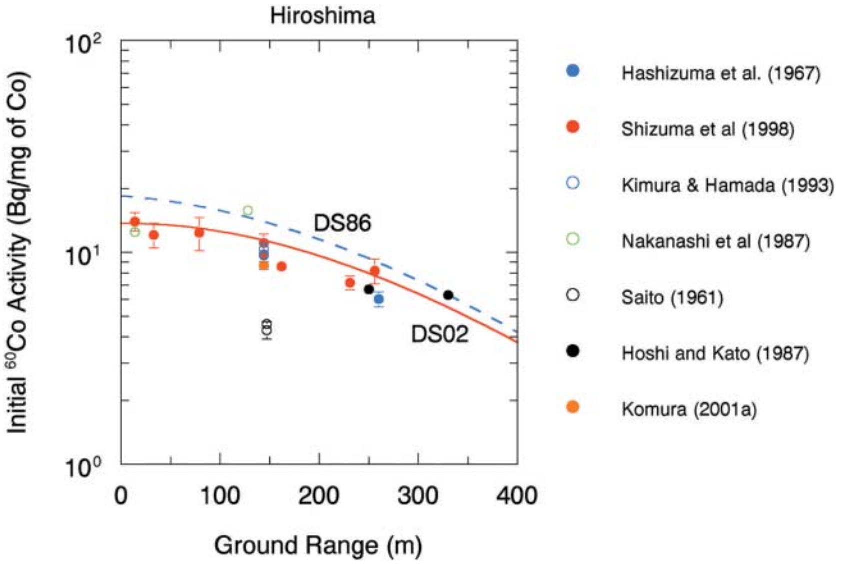

Figure 10. *Comparison of ^{60}Co measurements at Hiroshima with DS86 and DS02 calculations at close-in ground ranges of 400 m or less. The DS86 calculations assume a 580-m burst height and 15-kt yield at Hiroshima, and the DS02 calculations assume a 600-m burst height and 16-kt yield.*

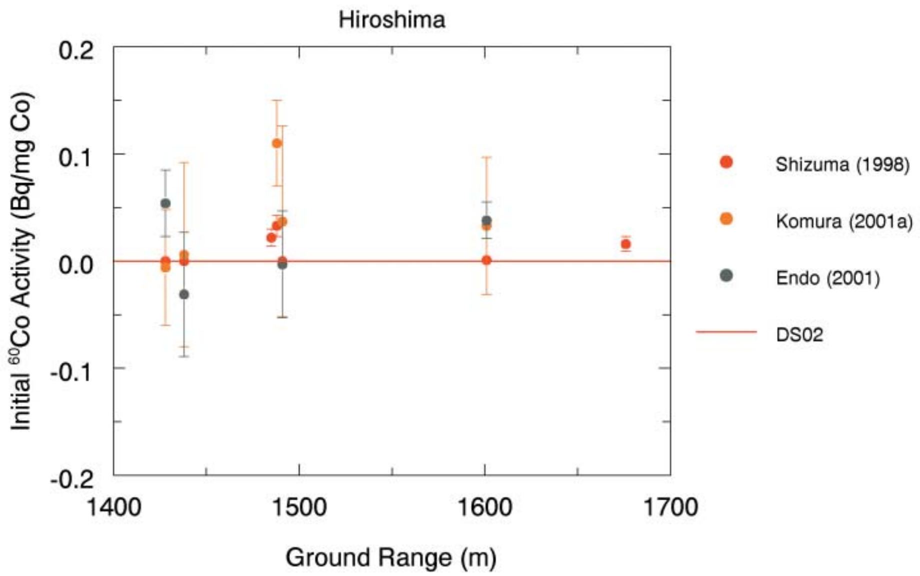

Figure 11. *Comparison of ^{60}Co measurements at Hiroshima with DS02 calculations at distant ground ranges of 1,300 m or more. The DS02 calculations assume a 600-m burst height and 16-kt yield at Hiroshima.*

Summary and Conclusions

The ^{60}Co measurements at Hiroshima and Nagasaki were reviewed and compared with the results of the new DS02 calculations for the two cities. Some corrections were made to previously published data from the 1965 measurements of JNIRS, ground ranges of all of the ^{60}Co measurements were reviewed and new ground ranges were determined when possible by transforming sample coordinates to the new city maps for Hiroshima and Nagasaki, and transmission factors were investigated for a number of samples used in the ^{60}Co measurements. Transmission factors were not calculated for all samples used in the ^{60}Co measurements but some general rules were given for estimating transmission factors for these samples. Experimental measurements of the background ^{60}Co activity from environmental neutrons were also reviewed, and it was found that the ^{60}Co background from environmental neutrons was not an important factor in the ^{60}Co measurements of bomb-induced activity at either city.

At Hiroshima, there was good overall agreement between the ^{60}Co measurements and DS02 calculations out to ground ranges of approximately 1,300 m with one exception. It appears that there was a problem with either the counter operation or calibration during some JNIRS measurements involving iron-ring samples at Hiroshima. The iron-ring measurements are based on only one measurement at each sample location, all of them performed in a single series of measurements between 29 September 1965 and 10 October 1965. The rebar measurements, on the other hand, were based on anywhere from 4 to 29 replicate measurements at each sample location, and most of the replicate measurements were done in such a way that earlier measurements were rechecked by later measurements in a different series, separated by several months in time. At ground ranges of more than 1,300 m at Hiroshima, there also appears to be a problem of distinguishing between sample counts and detector background. The estimated initial activities in the distant samples were dependent to some extent on both the detector used in the measurements and the method of determining count rates for the 1173- and 1333-keV gamma rays from ^{60}Co.

At Nagasaki, the ^{60}Co measurements were generally consistent with the DS02 calculations, but the measurements show a lot of scattering even at small ground ranges. Nagasaki type bombs were also detonated during a number of early weapon tests, and the neutron activation measurements at several of these tests have been investigated using the same DS02 calculational techniques. Small differences are observed between calculations and measurements for neutron activation at these weapon tests compared to the scattering observed between the ^{60}Co measurements and DS02 neutron calculations for Nagasaki. Nevertheless, all of the neutron activation measurements, including those for ^{60}Co, and all TLD measurements were systematically compared with the DS02 calculations at Nagasaki, and the analysis produced an overall best result for a height of burst and bomb yield that were very close to the 503-m and 21-kt values used previously for the Nagasaki explosion.

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