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Health and Safety Research Division

ACTIVATION OF COBALT BY NEUTRONS FROM THE HIROSHIMA BOMB

G. D. Kerr, F. F. Dyer, J. F. Emery, J. V. Pace III,
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Manuscript completed: September 26, 1989
Date published: February 1990

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Prepared for the
U.S. DEFENSE NUCLEAR AGENCY
Washington, D.C. 20305
Under Contract No. DNA 88-853 and
Interagency Agreement No. DOE 0046-A130-A1

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No. DE-AC05-84OR21400

MASTER

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ABSTRACT

A study has been completed of cobalt activation in samples from two new locations in Hiroshima. The samples consisted of a piece of steel from a bridge located at a distance of about 1300 m from the hypocenter and pieces of both steel and concrete from a building located at approximately 700 m. The concrete was analyzed to obtain information needed to calculate the cobalt activation in the two steel samples.

Close agreement was found between calculated and measured values for cobalt activation of the steel sample from the building at 700 m. It was found, however, that the measured values for the bridge sample at 1300 m were approximately twice the calculated values. Thus, the new results confirm the existence of a systematic error in the transport calculations for neutrons from the Hiroshima bomb.

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INTRODUCTION

Various radiation effects in the Japanese A-bomb survivors and their offspring have been investigated since 1948 by a cooperative U.S.-Japan research organization, known as the Radiation Effects Research Foundation (RERF). A reliable estimate of the radiation dose to each of the individual survivors is essential to the understanding and interpretation of the biological data from the various RERF investigations (Finch and Iwao, 1978). Without reliable dose estimates, a meaningful analysis of carcinogenic and genetic risk is not possible.

In 1983, joint U.S.-Japan research programs and oversight committees were established to conduct a thorough review of all aspects of the radiation dosimetry for the atomic bombs in Hiroshima and Nagasaki (RERF, 1983; RERF, 1984). The review was completed in 1986 and a final two-volume report was published (RERF, 1987) that discussed the physical basis for a new Dosimetry System 1986 (DS86). The DS86 estimates for the individual survivors replaced the so-called Tentative 1965 Doses (or T65D estimates) which served as a basis for risk analysis throughout the 1970's (Milton and Shohoji, 1968; Auxier, 1977).

While the dose reassessment is nearly complete, there remains a need for additional studies of neutron activated materials, particularly cobalt (National Research Council, 1987). Thus, samples from two new locations in Hiroshima have been studied in both Japan and the United States. The samples consisted of a piece of steel from a bridge at 1300 m and pieces of both steel and concrete from a building at 700 m. The concrete was analyzed to obtain data needed in calculations of the

cobalt activation in the steel samples. The Defense Nuclear Agency (DNA) funded Oak Ridge National Laboratory (ORNL) to make calculations and measurements as required in these combined U.S.-Japan studies.

DOSE REASSESSMENT STUDIES

One of the most significant changes of the dose reassessment studies involves the radiation fields in the open in Hiroshima (Kerr et al, 1987). The neutron kerms are much smaller than before, and the gamma-ray kerms are much greater, particularly at the larger ground ranges (Figure 1). The DS86 gamma-ray calculations are in close agreement with results of so-called thermoluminescent or TL measurements (Figure 2). The TL measurements are discussed in reports by Ichikawa and his colleagues (Ichikawa et al, 1966, and 1987; Hoshi et al, 1987) and the staff of the National Institute of Radiological Sciences (NIRS) in Japan (Hashizume et al, 1967; Maruyama et al, 1987).

A major task of the dose reassessment studies was to test the DS86 calculations to the extent feasible (National Research Council, 1987). The discrete ordinates code, DOT-4, was used in DS86 calculations (Kerr et al, 1987) and the DS86 values were compared extensively with those from other calculations using the TART Monte Carlo code (Mendelsohn, 1987). Because the two computer codes use different sets of evaluated cross-section data and also use very different techniques to obtain a solution to the Boltzmann transport equation, the results provided an added measure of confidence in the calculated values (Figure 3). In Hiroshima, the calculated values agreed to within about 10% for neutron kerma and 15% for activation of cobalt.

Figure 1. Comparison of DS86 and T65D values for the radiation fields in the open in Hiroshima.

Figure 2. Comparison of DS86 calculations and TL measurements of the gamma-ray kerma in the open in Hiroshima.

Figure 3. Comparison of DS86 calculations (Kerr et al, 1987) using the discrete ordinates code, DOT-4, with other calculations using the TART Monte Carlo code (Mendelsohn, 1987).

A major source of data for experimental testing of the DS86 neutron calculations is activation of cobalt by the $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ reaction (Hashizume et al, 1967; Hashizume, 1983). Some of the advantages of the experimental data for ^{60}Co are that its decay scheme is well known and relatively simple (Figure 4), the reaction cross section is also well known (Magurno et al, 1982), and ^{59}Co or stable cobalt is prevalent as a trace element in iron and steel (Figure 5). Extensive measurements have been made of the cobalt activation in steel reinforcing bars (or rebars) from various concrete structures in Hiroshima (Maruyama and Kawamura, 1987) and iron rings from the roofs of several large buildings (Figure 6). Because of attenuation in the concrete walls, the cobalt activation in the steel rebars was only half of that measured in the iron rings (Figure 7). The estimated uncertainties of the NIRS measurements ranged from 5% at the smallest ground ranges to 20% at the largest ground ranges (Hashizume et al, 1967; Kawamura et al, 1967).

A major disappointment of the dose reassessment was the poor agreement between the measurements and calculations for cobalt activation in Hiroshima (Figures 8 and 9). The calculated-to-measured ratios were always greater than one at ground ranges of 0 to 500 m and always less than one at ground ranges of 500 m and beyond (Figure 10). The rebar calculations by Loewe (1985) showed that the delayed neutrons made only a small contribution to cobalt activation in Hiroshima and his results were confirmed later by Dolatahshi et al (1987). Thus, it was concluded that the problem resided either with the prompt-neutron calculations or with the cobalt-activation measurements, especially those at the largest ground ranges (National Research Council, 1987).

Figure 4. Schematic of the decay scheme for ${}^{60}\text{Co}$.

Figure 5. Schematic showing location of steel samples in Hiroshima.

Figure 6. Picture showing the iron rings on roof of the Kodokan Building after the atomic bombing in 1945.

Figure 7. Data from ^{60}Co measurements made during the 1960's by the Japanese National Institute of Radiological Sciences.

Figure 8. Data on cobalt activation of iron rings from studies at the Japanese National Institute of Radiological Sciences (NIRS) and Lawrence Livermore National Laboratory (LLNL).

Figure 9. Data on cobalt activation of steel rebars from studies at the Japanese National Institute of Radiological Sciences (NIRS) and Lawrence Livermore National Laboratory (LLNL).

Figure 10. Calculated to measured ratios for cobalt activation in Hiroshima, using data from studies at Lawrence Livermore National Laboratory (LLNL), Japanese National Institute of Radiological Sciences (NIRS), and Science Applications International Corporation (SAIC).

CURRENT STUDY SAMPLES

Table 1 provides information on the locations of the samples used in the current study. The steel sample from the Yokogawa Bridge was located at an optimum range of about 1300 m. At this range, the discrepancy between calculations and measurements had grown to something like a factor of four to five (Figure 10). To verify results, it was also important to have a steel sample at a range where the discrepancy was small. Thus, a second steel sample and a concrete sample from the Chugoku Electric Company were included in the current study. The concrete was analyzed to obtain information needed to calculate the cobalt activation in the steel samples. The Chugoku Electric Company is shown in Figure 11, and the Yokogawa Bridge in Figure 12.

Concrete Sample: Hiroshima is located on several islands formed by the delta plane of the Ota River. Dredgings from the river and its distributaries were used extensively for both landfill and construction in Hiroshima (USSBS, 1947, Vol. 3, p. 36). The sand used in concrete was unscreened normally, but the gravel was screened to obtain some gradation, with maximum sized stones of about 5 cm.

An earthquake in 1923 caused such severe damage to all types of structures in Japan that a very strict building code was adopted in 1924 (USSBS, 1947, Vol. 2, p. 98).

Steel-frame and reinforced-concrete buildings were limited to a height of 30 m. The concrete-reinforced buildings were also to be designed as close to a monolithic unit as was possible.

Wood-frame and brick buildings were limited to an overall height of about 13 m and 10 m at the eaves. The maximum length of an unsupported wall also was set at 10 m.

Table 1. Sample list for current study.

Sample description	Sample location	Ground range (m)
Concrete sample	44.36 × 60.97 ^a	676 ^b
Handrail sample	44.38 × 60.96	687
Bridge sample	43.88 × 63.06	1295

^aSample locations are specified in terms of a set of east-west and north-south coordinates on a Hiroshima map from Series L902 of the U.S. Army Map Service, Number 138,499 (June 1946).

^bDistance from the hypocenter of the bomb (Figure 5).

Figure 11. Picture showing the main entrance on west side of the Chugoku Electric Company after the bombing in 1945.

Figure 12. Picture showing the west elevation of the Yokogawa Bridge after the bombing in 1945.

Restrictions on the use of brick and similar materials of construction were so severe that bricks, concrete blocks, hollow tiles, or cut stones were seldom used after 1924 (USSBS, 1947, Vol. 2, p. 98).

Construction on the headquarters and main office building for the Chugoku Electric Company was started in 1929. The building was a reinforced-concrete structure which conformed to the strict Japanese building codes (USSBS, 1947, Vol. 2, pp. 222-224). It had five stories with a basement and a penthouse as shown in Figures 11 and 13. A stucco was applied to the exterior walls to give the appearance of cut pink-granite blocks (Joint Commission, 1951, Vol. 6, p. 149). The building was used as the main offices and headquarters for the Chugoku Electric Company until it was demolished in 1985.

Figure 14 shows the sample of concrete from a wall between first-floor windows on the north side of the building. The thicknesses of the fine-aggregate (stucco layer) and coarse-aggregate (normal layer) were about 3.3 cm (1.3 inches) and 7.6 cm (3.0 inches), respectively. The diameter of the steel rebar was 0.95 cm (0.375 inch) and it was centered within the coarse aggregate so that the total depth from the outer wall surface was about 7.1 cm (2.8 inches). The total thickness of the concrete and plaster in the walls between windows was only about 15 cm (6.0 inches), whereas the total thickness of the concrete and plaster in the load bearing walls of the building was about 38 cm (15 inches).

Handrail Sample: Figure 15 shows a photograph of the handrail sample and Table 2 provides information on its physical characteristics. The sample was cut from a stand at the top of the smokestack of the Chugoku

Figure 13. Schematic the showing construction of the Chugoku Electric Company and its dimensions in feet and inches (1' equals 30.48 cm and 1" equals 2.54 cm).

Figure 14. Picture of concrete sample from a wall section between first-floor windows on the north side of Chugoku Electric Company.

Figure 15. Picture of the handrail sample from the stand at the top of the smokestack of the Chugoku Electric Company.

Table 2. Physical characteristics of handrail sample.

Part	Dimensions (cm)	Mass (g)^a
Bottom rail plate	48 × 10.2 × 1.27	4637
Top horizontal rod	46 × 2.22 diam	1258
Right vertical rod	65 × 1.91 diam	1362
Left vertical rod	65 × 1.91 diam	1355

^aMeasured after dissection of the sample and cleaning of the parts by sandblasting. The mass of the sample before dissection and cleaning was approximately 9.1 kg (20 pounds).

Electric Company (Figure 16). A study of the damage to stacks in Hiroshima was reported in Volume 3 of the 1947 USSBS report (pp. 308-321) but they disregarded the stack of the Chugoku Electric Company (Stack No. 49) because its construction was different from that of most other stacks in Hiroshima (pp. 310-311). However, the stand on the smokestack of the Chugoku Electric Company was identical to the one shown in Figure 17 (Stack No. 9, p. 312).

Bridge Sample: Figure 18 shows the Yokogawa Bridge following its construction over the Tenma River in 1922 (USSBS, 1947, Vol. 3, Bridge No. 27, p. 32). The bridge connected the Hiroshima wards of Terra-machi and Yokogawa-machi, and it served both pedestrian and highway traffic until it was demolished in 1983 (Figure 19). The construction of the bridge is summarized in Figure 20 (USSBS, 1947, Vol. 3, p. 118) and Table 3 (USSBS, 1947, Vol. 3, p. 132).

The steel sample from the Yokogawa Bridge is shown in Figure 21. It was disassembled by removal of the rivets, and the resulting plate and angle pieces were sandblasted to remove rust and paint. Because the sample had been removed from the bridge by a cutting torch, thin sections about 3-mm to 9-mm wide were trimmed from the burned edges to avoid the possibility that the trace element content of the steel was altered by the high temperature. The larger sections were then sawed into smaller pieces as shown in Figure 22. For ease of reference, the various bridge-sample sections were labeled with an "A" for the 0.64-cm plate, "B" for the angle iron, "C" for the 1.27-cm plate in contact with the angle iron, and "D" for the 1.27-cm plate in contact with the

Figure 16. Picture showing the north wall and the smokestack of the Chugoku Electric Company as viewed from the hypocenter of the bomb (see building in the foreground on the right-hand side of the photograph).

Figure 17. Picture showing a stand identical to the one mounted on the smokestack of the Chugoku Electric Company.

Figure 18. Picture showing the Yokogawa Bridge after its construction in 1922.

Figure 19. Picture showing the Yokogawa Bridge before its demolition in 1983.

Figure 20. Schematic showing the construction of the Yokogawa Bridge and its dimensions in feet and inches (1' equals 30.48 cm and 1" equals 2.54 cm).

Table 3. Construction details for the Yokogawa Bridge.

Detail	Remarks
Design:	Steel arch (USSBS, 1947, Vol. 3, Bridge No. 27, p. 132).
Spans:	Single span with a length of 61 m.
Materials:	Main girders were boxed chords. ^a Decking was reinforced concrete with an asphalt wearing surface. Abutments were concrete.
Special features:	Tied arch at anchorage with 20-cm by 13-cm I-beam suspenders for support of decking and no diagonal bracing.
Other features:	Water main (25-cm diam) carried under the decking of bridge (USSBS, 1947, Vol. 3, Bridge No. 27, p. 132; Fujita, 1988). Gas main (20-cm diam) carried on the west side of bridge (USSBS, 1947, Vol. 3, Bridge No. 27, p. 295; Fujita, 1988). Telephone cables carried on the east side of bridge (Fujita, 1988).

^aFigure 20 from the 1947 USSBS report shows three 0.5-inch plates on the top and bottom of the main girders. There were, however, only two 0.5-inch plates on the top and bottom of the main girders as shown by the photographs in Figures 21 and 22.

Figure 21. Picture of sample cut from top of arch on the east side of the Yokogawa Bridge.

Figure 22. Picture of the bridge sample after dissection and cleaning by sandblasting.

"C-plate" (Table 4). Small pieces also were cut from the various bridge-sample sections and later analyzed for elemental cobalt and other chemical constituents.

To remove contamination that may have been introduced by sand-blasting and sawing, the pieces were etched for two 20-min periods in warm hydrochloric acid solutions that were 3 molar in HCl. After being etched, the steel pieces were rinsed in hot water, dried, and sealed in plastic bags. By rinsing the pieces in a stream of hot water and blotting them with absorbent paper, they dried very rapidly and showed almost no subsequent formation of rust. The handrail pieces were sandblasted and cleaned in the same manner as the bridge parts.

ELEMENTAL ANALYSES

Analyses were made to determine the elemental composition for all major components of the concrete, handrail, and bridge samples. The primary technique for obtaining data on a sample was inductively coupled plasma-atomic emission spectrometry (ICP-AES). Other techniques were used as required to obtain data on a few additional elements or to verify the data on a specific element, particularly cobalt. These other techniques included flame-excited atomic absorption spectrometry (AAS), neutron activation analysis (NAA), and inductively coupled plasma-mass spectrometry (ICP-MS). The NAA measurements were made by R. M. Lindstrom of the National Institute of Standards and Technology (NIST), the ICP-MS measurements by M. R. Smith of the Pacific Northwest Laboratories (PNL), and the AAS and ICP-AES measurements by staff members at ORNL, principally N. M. Ferguson and J. M. Keiler.

Table 4. Physical characteristics of bridge sample.

Part	Dimensions (cm) ^a	Mass (g) ^b
A-plate	24 × 40 × 0.64	
A1		928.4
A2		1020.0
A3		1029.9
A4		970.1
Al-sample		45.4
Edge trim		204.7
B-angle	24 × 15.2 × 10.2 × 1.27	
B1		1026.2
B2		1417.7
B3		1305.1
B4		1048.4
B3-sample		69.8
Edge trim		329.5
C-plate	24 × 32 × 1.27	
C1		1550.4
C2		1528.8
C3		1503.1
C4		1623.1
C3-sample		71.0
Edge trim		398.6
D-plate	24 × 32 × 1.27	
D1		1456.6
D2		1497.9
D3		1581.6
D4		1472.5
D4-sample		70.0
Edge trim		778.6
Rivets	2.54 diam	
R1		283.3
R2		268.6
R3		344.8
R4		301.6
R5		206.7 ^c

^a Approximate values measured before dissection of the sample.

^b Measured after dissection of the sample and cleaning of the parts by sandblasting. The mass of the sample before dissection and cleaning was approximately 26 kg (57 pounds).

^c Head of rivet was missing (Figures 21 and 22).

Steel Samples: The first measurements on the steel samples from Hiroshima were made by ICP-AES using a Jobin Yvon Multichannel Instrument, Model J 48, and AAS using a Perkin Elmer Instrument, Model 5000AA. The procedure used in the ICP-AES measurements was similar to the method described by Brenner et al (1987) and the procedure used in the AAS measurements was similar to method 219.7 described by the Environmental Protection Agency (1979). The instruments were calibrated using either NIST Standard Reference Materials (SRM's) or commercially available materials that were traceable to NIST SRM's.

In the ICP-AES and AAS measurements, a specimen of about two grams from each steel sample was placed in a 20-mL solution of 6-molar hydrochloric acid. After the samples had dissolved, the solutions contained a black residue believed to be carbon along with some oxides of silicon. The residues and solutions of each sample were separated and each was analyzed for cobalt. In the separations, the samples were centrifuged and the supernates were decanted. The residues were washed three times. Each wash solution was centrifuged and the wash supernate was added to the original supernate. The residues were dissolved using hydrochloric, nitric, and hydrofluoric acids, and the resulting solution was diluted to 50 mL and analyzed by ICP-AES. No significant amount of cobalt was found in the residues. Thus, the original supernates of each of the samples were diluted to 50 mL and small aliquots were taken for analysis on both the ICP-AES and AAS instruments.

In addition to the steel samples from Hiroshima, four other steel samples were included in the study (Table 5). Two of the samples were used in later cobalt-activation measurements to establish the background

Table 5. Concentrations of stable cobalt in steel samples in parts per million (ppm).

Sample description	AAS Measurements		ICP-AES Measurements		NAA Measurements	ICP-MS Measurements
	(#1)	(#2)	(#1)	(#2)		
NIST reference steel samples						
AISA 4340 steel (SRM-361)	282	287	293		278 (± 2)	
Low carbon steel (SRM-131c)	140		136			
Rebar from Hiroshima	86	89	109			
Handrail from Hiroshima						
Bottom rail plate	63	64	90	85	89 (± 1)	92 (± 1)
Top horizontal rail	87		106		110 (± 1)	
Right vertical rail	134	120	149		191 (± 1)	167 (± 6)
Left vertical rail	216		224		194 (± 1)	180 (±12)
Bridge frame from Hiroshima						
A-plate (0.25-inch thick)	288		288			
B-angle (0.50-inch thick)	193		208			
C-plate (0.50-inch thick)	235	227	251		245 (± 2)	242 (± 1)
D-plate (0.50-inch thick)	182		186		193 (± 1)	197 (± 1)
Background counting samples						
ALCOA-Maryville steel				46	49 (± 1)	49 (± 1)
Homestake Mine steel						30 (± 2)

counting rates and two reference steel samples were used in current measurements to establish the precision of the stable cobalt data for the Hiroshima samples. SRM-361 was an AISA 4340 steel with a certified value for cobalt of 0.032 percent by mass (320 ppm) and SRM-131c was a low carbon steel with an uncertified value for cobalt of 0.002 percent by mass (20 ppm). These two NIST SRM's were selected to bracket the cobalt concentrations of normal steels.

The initial AAS and ICP-AES measurements gave results that were highly ambiguous (Table 5). First, values of 282 to 293 ppm (mean of 287 ppm) were measured for the cobalt concentration in the NIST reference steel sample, SRM-361. The certified value for cobalt was 320 ppm or 0.032 percent by mass with an estimated fractional standard deviation of approximately 3%. Next, a value for cobalt of about 140 ppm was obtained for the low carbon steel, SRM-131c. It was verified by NIST that the uncertified value for cobalt should have been 0.02 percent by mass (200 ppm) and the higher value from original data sheets was probably due to the round-off of a smaller number such as 0.014 percent by mass (140 ppm). Finally, the AAS measurements gave repeatable results (Series Nos. 1 and 2 in Table 5), but they were consistently lower than those obtained from multichannel ICP-AES measurements on samples with small cobalt concentrations (Series No. 1 in Table 5). The multichannel ICP-AES result for the bottom rail plate was checked by scanning ICP-AES measurements made on a Perkin Elmer Instrument, Model 6500XR (Series No. 2 in Table 5).

The next measurements on the Hiroshima steel samples were carried out at NIST using standardized NAA techniques (Lindstrom 1988). Neutron

irradiations were made for one hour in a thermal neutron flux of approximately $2 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$. Samples with masses of 100 to 200 mg were irradiated along with an evaporated cobalt-solution standard and SRM-361. The SRM-361 and Hiroshima samples were treated as unknowns in the analyses. After a three-day period of decay, the various samples were counted at a distance of 10 cm from a 95-cm³ germanium detector for two hours, long enough to obtain values with fractional standard deviations of less than 1% for the cobalt concentrations of most samples. In general, the NAA values were in close agreement with the ICP-AES values for stable cobalt (Table 5) and the elemental data from these two sets of measurements were adopted with a preference given to the NAA values for cobalt if available (Table 6). The carbon concentrations were obtained by standard chemical techniques using a LECO Carbon Analyzer, Model IR 212 .

The final ICP-MS measurements were made at PNL using a VG Instruments PlasmaQuad System in which sampling of the steel specimen was accomplished by laser ablation. By pulsing the laser, it was possible to make repeated measurements on a steel specimen within a short period of time. The procedure was similar to that used by Arrowsmith (1987). The means and fractional standard deviations as determined from repeated measurements on various steel samples are given in Table 5 (Brodzinski, 1988). For the vertical rods from the handrail sample, the fractional standard deviations are quite large and suggest that the samples are not very homogeneous. The poor agreement noted in the cobalt values for the vertical rods suggested that they were made of junk steel (i.e., steel containing large amounts of scrap iron).

Table 6. Composition of steel samples in parts per million (ppm).

Element	Method	Handrail Sample		Bridge Sample		
		Plate	Average ^a	C-plate	D-plate	Average ^a
Antimony (Sb)	NAA	7.15E+00	5.54E+01	5.22E+00	7.71E+00	6.46E+00
Arsenic (As)	NAA	5.63E+01	1.94E+02	5.15E+01	4.22E+01	4.68E+01
Barium (Ba)	ICP-AES	4.10E+01	3.37E+01	3.80E+01	2.40E+01	3.35E+01
Cadmium (Cd)	ICP-AES	2.80E+01	4.87E+01	5.10E+01	5.00E+01	5.05E+01
Carbon (C)	LECO		8.00E+02	6.40E+02	8.30E+02	8.40E+02
Chromium (Cr)	NAA	9.98E+01	1.92E+02	3.99E+01	4.62E+01	4.30E+01 ^b
Cobalt (Co)	NAA	8.90E+01	1.46E+02	2.45E+02	1.93E+02	2.33E+02 ^b
Copper (Cu)	ICP-AES	7.70E+02	1.66E+03	4.30E+03	2.80E+03	4.00E+03
Iron (Fe)	NAA	9.79E+05	9.96E+05	9.73E+05	9.67E+05	9.70E+05
Lanthanum (La)	NAA	4.60E-03	5.45E-03	7.70E-03	1.14E-02	9.55E-03
Manganese (Mn)	ICP-AES	3.50E+03	3.50E+03	3.30E+03	4.00E+03	3.67E+03
Nickel (Ni)	ICP-AES	1.50E+02	2.27E+02	2.80E+02	2.30E+02	2.70E+02
Silicon (Si)	ICP-AES	5.50E+02	4.23E+02	4.80E+02	3.00E+02	4.77E+02
Zinc (Zn)	ICP-AES	8.50E+00	1.35E+01	1.80E+01	1.80E+01	1.70E+01
Total		9.34E+05	1.00E+06	9.82E+05	9.76E+05	9.80E+05

^aAverage of all measured values for various sample components (Tables 2 and 4).

^bAverage of the four ICP-AES values for the bridge sample (Table 5).

Concrete sample: The concrete sample consisted of a normal layer of coarse rock and sand and a stucco layer of fines (Figure 14). The stucco layer was separated from the normal layer and treated as a separate sample. The concrete samples were dried to a constant mass at temperatures of 105 to 110°C, and then ground to less than 100 mesh using a shatter box. Standard chemical methods were used to obtain data on a few elements such as H, C, N, O, and Si (Table 7). Portions of the samples also were dissolved by nitric acid-hydrofluoric acid digestion and a lithium-borate fusion. The solutions were then analyzed by ICP-AES to obtain data on various other elements in the concrete samples (Table 7).

The elemental composition of the coarse aggregate was assumed to be typical of concrete used for ordinary construction in Hiroshima prior to 1945 (USSBS, 1947, Vol. 3, p. 36). Because the concrete sample was stored indoors in a dry environment for several years, it was necessary to make an estimate of the free water content of the concrete under more normal conditions. A free water content of 5% was adopted from available data on similar concretes (Nuclear Regulatory Commission, 1984). The data in Table 7 were also renormalized to obtain the composition for totally dry concrete and the oxygen content was then increased so that the sum for all constituents was 100%. Table 8 compares the resulting composition to other data on a concrete sample from the Joyama Primary School in Nagasaki (Maruyama, 1987).

A problem with the previous calculations for cobalt activation of steel rebars in Hiroshima has been a lack of data on trace elements in concrete, particularly boron (Loewe et al, 1987). Boron has a large

Table 7. Composition of concrete sample from Hiroshima.

Element	Coarse Aggregate	Fine Aggregate	Analytical method
Aluminum (Al)	6.60%	4.40%	ICP-AES
Calcium (Ca)	5.00	11.00	ICP-AES
Carbon (C)	0.90	1.60	Gravimetric
Hydrogen (H)	0.18	0.40	Gravimetric
Iron (Fe)	1.70	1.30	ICP-AES
Magnesium (Mg)	0.48	0.33	ICP-AES
Nitrogen (N)	0.01	0.06	Gravimetric
Oxygen (O)	47.50	45.70	14-MeV neutrons
Silicon (Si)	29.20	25.20	Gravimetric
Sodium (Na)	1.90	1.00	ICP-AES
Titanium (Ti)	0.16	0.14	ICP-AES
Antimony (Sb)	15 ppm	≤6 ppm	ICP-AES
Arsenic (As)	11	10	ICP-AES
Barium (Ba)	440	360	ICP-AES
Beryllium (Be)	1.7	1.3	ICP-AES
Boron (B)	21	≤16	ICP-AES
Cadmium (Cd)	1.8	1.0	ICP-AES
Chromium (Cr)	36	20	ICP-AES
Cobalt (Co)	4.2	4.4	ICP-AES
Copper (Cu)	23	20	ICP-AES
Lead (Pb)	26	14	ICP-AES
Lithium (Li)	64	44	ICP-AES
Manganese (Mn)	470	270	ICP-AES
Nickel (Ni)	3.9	5.4	ICP-AES
Phosphorus (P)	260	210	ICP-AES
Strontium (Sr)	160	140	ICP-AES
Vanadium (V)	33	22	ICP-AES
Zinc (Zn)	71	78	ICP-AES
Zirconium (Zr)	58	43	ICP-AES
Moisture	0.57%	2.10%	Drying at 110°C
Total	94.37%	93.36%	

Table 8. Comparison of concrete from Hiroshima and Nagasaki.

Element	Grams per kilogram of concrete	
	Hiroshima	Nagasaki
Hydrogen	5.6	5.9
Lithium	0.06	-
Beryllium	0.002	-
Boron	0.02	0.08
Carbon	8.6	8.0
Nitrogen	0.1	-
Oxygen	553	532
Sodium	18.2	18.3
Magnesium	4.6	8.2
Aluminum	63.2	52.5
Silicon	280	246
Phosphorus	0.25	0.66
Sulfur	-	1.1
Potassium	-	10.3
Calcium	47.9	85.6
Vanadium	0.03	-
Titanium	1.5	-
Chromium	0.03	0.21
Manganese	0.45	0.62
Iron	16.2	25.7
Cobalt	0.004	-
Nickel	0.004	0.04
Copper	0.022	-
Zinc	0.068	-
Arsenic	0.010	-
Strontium	0.15	-
Zirconium	0.055	-
Cadmium	0.002	-
Barium	0.42	-
Lead	0.025	-
Antimony	0.014	-

cross section for capture of thermal neutrons and the boron content of concrete caused the cobalt activation in the rebars to vary as shown in Figure 23. If the previous rebar calculations are adjusted to the boron content in concrete from Hiroshima (0.02 mg per kg of concrete), the agreement becomes worse, instead of better, at all ground ranges (Figure 10). At 1180 m, for example, the adjusted rebar values are approximately 30% greater and 10% less than the previously calculated values of Loewe (1985) and Dolatshahi et al (1987), respectively. The composition of concrete from Nagasaki was used in Loewe's calculations for rebars in Hiroshima (Figure 23), while a concrete without any boron was assumed in the calculations by Dolatshahi et al (1987). Careful recalculations are needed for the rebar samples using the composition for Hiroshima-type concrete in Table 8.

COBALT-60 MEASUREMENTS

The first cobalt-60 measurements were made at ORNL using a 113-cm³ germanium (Ge) detector that was well-shielded physically (Detector 5). It was possible to easily detect ⁶⁰Co in the handrail sample (Figure 24), and with some difficulty, to also detect ⁶⁰Co in the bridge sample (Figure 25). However, the counting efficiency of the Ge detector was too low, and its background was too high, to allow quantitative measurements of the ⁶⁰Co in the bridge sample (Figures 25 and 26).

The next cobalt-60 measurements were made at PNL using pairs of 15000-cm³ NaI(Tl) detectors that were operated in coincidence and also shielded electronically by the use of very large plastic phosphor anticoincidence detectors (Wogman and Brodzinski, 1973). Such systems

Figure 23. Effect of boron content of concrete on cobalt activation of steel rebar at a ground range of 1180 m in Hiroshima.

Handrail sample from Hiroshima

Counted for 240000 s starting on 2/5/88

Figure 24. Gamma-ray spectrum from preliminary ORNL measurements of ^{60}Co in handrail sample from Hiroshima (Detector 5).

Bridge sample from Hiroshima

Counted for 240000 s starting on 2/14/88

Figure 25. Gamma-ray spectrum from preliminary ORNL measurements of ^{60}Co in bridge sample from Hiroshima (Detector 5).

Background radiation

Counted for 400000 s starting on 2/18/88

Figure 24. Detector background for preliminary ORNL measurements of ^{60}Co in bridge sample from Hiroshima (Detector 5).

are well suited to counting of ^{60}Co which emits two gamma rays that can be detected simultaneously in the two NaI(Tl) detectors (Figure 4). Coincidence counting of the two gamma rays from ^{60}Co makes it possible to ignore an electronic pulse produced by a single gamma-ray interaction in either of the two NaI(Tl) detectors. In addition, pulses that occur in one (or both) of the NaI(Tl) detectors at the same time as a pulse in the plastic phosphor anticoincidence shields can also be ignored (Figure 27). It was possible, therefore, to achieve both a low background and a high counting efficiency for ^{60}Co . Two of the plates from the bridge and the bottom plate from the handrail were counted using two such detector systems at PNL (Systems 8 and 9). To establish the background on the two different detector systems, measurements were also made using other steel plate samples: one from a light steel-frame building erected in the early 1940's at the Aluminum Company of America, ALCOA-Maryville, Tennessee, and another from an old rail track at the Homestake Mine, a deep underground mine in South Dakota (Tables 5 and 9). The background rates were one count every 15 minutes on Detector System 8 and one count every 28 minutes on Detector System 9 (Table 9).

Each of the steel plates used in the PNL measurements weighed about 4 kg (9 pounds) and measured about $20.3 \times 20.3 \times 1.27$ cm ($8 \times 8 \times 0.5$ inches). Figure 15 shows the handrail sample before it was cleaned and dissected, and Figure 28 shows the shaded portions of the bottom rail plate that were counted in the spring of 1988 (Table 9). This plate was used as dissected originally, except the four large holes were plugged with pieces machined from the unshaded portion of the sample to the right of Figure 28. The C- and D-plates from the bridge sample were not usable as dissected originally (Figure 22). Thus, the two plates

Figure 27. Schematic of detector systems used in PNL measurements of ^{60}Co in steel samples from Hiroshima (Systems 8 and 9).

Table 9. Summary of gross count-rate data from PNL measurements.

Detector system	Starting date	Sample description	Mass (kg)	Gross counts	Time (min)	Gross count rate (cpm $\pm$ SD)
#8	5/10/88	C-plate from bridge	4.031 ^a	1892	18340	0.1032 $\pm$ 0.0024
#9	9/27/88		3.777 ^b	439	8025	0.0535 $\pm$ 0.0026
#8	11/09/88		3.777 ^b	1001	11193	0.0894 $\pm$ 0.0028
#9	11/17/88		3.777 ^b	470	8127	0.0575 $\pm$ 0.0027
#8	11/23/88		3.712 ^c	795	9549	0.0833 $\pm$ 0.0030
#9	11/30/88		3.712 ^c	496	9674	0.0513 $\pm$ 0.0023
#9	5/13/88	D-plate from bridge	3.980	1090	15265	0.0717 $\pm$ 0.0022
#9	11/08/88		3.500 ^c	848	11984	0.0708 $\pm$ 0.0024
#8	11/17/88		3.500 ^c	771	8354	0.0923 $\pm$ 0.0033
#8	6/04/88	Bottom rail plate	3.892	5346	4016	1.3312 $\pm$ 0.0182
#9	6/07/88		3.892	13639	10605	1.2861 $\pm$ 0.0110
#8	6/07/88	ALCOA-Maryville steel	3.883 ^a	841	10972	0.0766 $\pm$ 0.0026
#9	9/19/88		4.108 ^d	345	9512	0.0363 $\pm$ 0.0020
#9	11/23/88	Homestake Mine steel	4.125	337	9341	0.0361 $\pm$ 0.0020 ^e
#8	11/30/88		4.125	633	9818	0.0645 $\pm$ 0.0026 ^e

^aSamples were contaminated during preparation for counting.

^bCount of sample after surfaces were dressed by machining.

^cCount of sample after surfaces and edges were both dressed by machining.

^dSecond ALCOA-Maryville sample prepared for counting at PNL.

^eCounts of this sample were used as the background rates for the two detector systems.

0 5 10
CENTIMETERS

Figure 28. Schematic of bottom rail plate with shading to indicate portions of dissected sample used in PNL measurements.

were recut as shown in Figure 29, and the shaded portions were also counted in the spring of 1988 (Table 9). It was later discovered that the C-plate from the bridge and the first ALCOA-Maryville sample had been contaminated during preparation for counting. Thus, the surfaces of the C-plate were dressed by machining, a second ALCOA-Maryville sample was prepared, and the two samples were recounted in the summer of 1988 (Table 9). Both the C- and D-plates were also recounted several times in the fall of 1988, and the Homestake Mine sample was included in the PNL measurements (Table 9). The Homestake Mine sample was helpful in establishing the fact that neutrons produced by cosmic rays did not contribute significantly to the cobalt activation of the bridge sample (Brodzinski, 1988).

Initially, it was planned to chemically separate the cobalt from all of the samples and then to measure the specific activity of the separated cobalt from each sample as had been done previously by Hashizume and his colleagues at NIRS (Hashizume et al, 1967; Kawamura et al, 1967; Maruyama and Kawamura, 1987). It was found, however, that the ^{60}Co in the samples could be determined with good counting statistics by nondestructive measurements at PNL (Table 10). To convert these count rate data to disintegration rates, it was necessary to make a specific activity measurement using only one of the samples counted at PNL. Thus, the bottom rail plate was used to minimize the effort involved in making a reliable determination of the specific activity in the sample.

The cobalt was separated by dissolving a 1-kg piece of the bottom rail plate in HCl, oxidizing the iron to Fe^{+3} , absorbing the Fe^{+3} and Co^{+2} on a Dowex-1 resin at 9-molar HCl, and eluting the Co^{+2} from the

Figure 29. Schematic of D-plate from bridge with shading to indicate portions of dissected sample used in PNL measurements.

Table 10. Summary of net count-rate data from PNL measurements.

Sample description	Detector system	Starting date	Mass (kg)	Cobalt (mg)	Decay factor	Net count rate (cpm/mg of Co $\pm$ SD) ^a
Bottom rail plate	#8	6/04/88	3.892	346 ^b	0.978 ^c	$(3.58 \pm 0.05) \times 10^{-3}$
	#9	6/07/88	3.892	346	0.980	$(3.54 \pm 0.03) \times 10^{-3}$
	Weighted Mean ^d					$(3.56 \pm 0.02) \times 10^{-3}$
D-plate from bridge	#9	5/13/88	3.980	768	0.971	$(4.47 \pm 0.37) \times 10^{-3}$
	#9	11/08/88	3.500	675	1.036	$(5.32 \pm 0.48) \times 10^{-3}$
	#8	11/17/88	3.500	675	1.039	$(4.28 \pm 0.65) \times 10^{-3}$
Weighted Mean						$(4.70 \pm 0.31) \times 10^{-3}$
C-plate from bridge	#9	9/17/88	3.777	925	1.020	$(1.92 \pm 0.36) \times 10^{-3}$
	#8	11/09/88	3.777	925	1.037	$(2.80 \pm 0.43) \times 10^{-3}$
	#9	11/17/88	3.777	925	1.039	$(2.41 \pm 0.37) \times 10^{-3}$
	#8	11/23/88	3.712	909	1.042	$(2.15 \pm 0.45) \times 10^{-3}$
	#9	11/30/88	3.712	909	1.045	$(1.75 \pm 0.35) \times 10^{-3}$
Weighted Mean						$(2.16 \pm 0.18) \times 10^{-3}$

^aValues normalized arbitrarily to August 6, 1988.

^bMass of elemental cobalt in sample based on the NAA data in Table 5.

^cFactor used to correct for decay between midpoint date of each count and August 6, 1988.

^dEach individual count was given a weight proportional to the reciprocal of the square of its standard deviation.

Dowex-1 with 4-molar HCl. The Dowex-1 was pretreated with 9-molar HCl before the process was begun, and the Fe^{+2} was oxidized to Fe^{+3} by adding nitric acid to the HCl solution containing the dissolved sample. The excess nitric acid was eliminated by distillation, and the HCl solution was adjusted carefully to 9 molar before the Fe^{+3} and Co^{+2} were absorbed on the Dowex-1. After the Co^{+2} was eluted from the Dowex-1, the Fe^{+3} was removed with 0.5-molar HCl, and the process was repeated. It was possible to process only 17 g of dissolved steel per day in an ion exchange column containing 500 g of the Dowex-1 resin. Thus, five columns were used and approximately 85 g of the dissolved steel were processed each day.

A total of eight days were needed to prepare the various acid solutions and to separate the cobalt from 425 g of the dissolved steel sample. The various acid solutions required the use of approximately one liter of nitric acid, 30 L of 12-molar HCl, and 35 L of highly purified water. It needs to be noted that the water was prepared by treating singly distilled water with a Millipore Milli-Q Filter System. The treated water had a resistance of 1.8×10^7 ohm cm and trace elements were not detectable by the ICP-AES method. It also needs to be noted that the solutions were prepared using Bakers Reagent Grade - Instra Analyzed Acids. These acids were batch analyzed by the Bakers Chemical Company, and the results were specified on each bottle. The specification on the bottles indicated that the elemental cobalt was less than 0.2 parts per billion (ppb). Thus, the various acid solutions were estimated to add an insignificant amount of elemental cobalt to the separated product sample (i.e., 0.01 to 0.1 mg).

The final cobalt-60 measurement was made at ORNL using a Ge detector with a volume of 85 cm³ and a well of 4 cm³ for the highly efficient counting of small samples (Detector B). To use the well, the detector was calibrated with mixed radiation sources in an Amersham Standard Solution that was diluted very carefully to 3 cm³. The separated product was then reduced by distillation to the same volume (i.e., 3 cm³) and counted for 10.3 days to obtain the disintegration rate of ⁶⁰Co to within one standard deviation of $\pm 5\%$ (Table 11). The elemental cobalt in the condensed product sample was measured easily by both the AAS and ICP-AES methods. From these data, it was determined that the specific activity was 0.0859 dpm per mg of Co if the data were normalized to the start of the cobalt-60 measurement on November 21, 1988, or 0.0893 dpm per mg of cobalt if the data were normalized arbitrarily to August 6, 1988 (Table 11). It also was possible to establish the counter efficiency for the PNL measurements and the specific activity of the cobalt in the C- and D-plates from the bridge (Table 10). The counter efficiency was (3.99 ± 0.24) percent or about one count per 25 disintegrations in the 4-kg plates, and the specific activities were $(5.42 \pm 0.60) \times 10^{-4}$ dpm per mg of Co in the C-plate and $(1.18 \pm 0.11) \times 10^{-3}$ dpm per mg of Co in the D-plate on August 6, 1988. A factor of 285 was used to extrapolate these specific activities back to the time of bombing on August 6, 1945 (Table 12). The results are found to be in excellent agreement with the recently reported results of an independent Japanese study (Kimura et al, 1989).

An extremely difficult problem to address experimentally was the background activation due to neutrons produced by cosmic rays (Hajal, 1989; Nakamura et al, 1987; O'Brien et al, 1978). Calculations indicate

Table 11. Summary of data for ORNL measurements of the specific activity in bottom rail plate.

Parameter	Comments
Counting system	Detector B
Counting time	14,838 min
Starting date	11/21/88
Mass of steel	~425 g
Mass of cobalt	33.3 mg ($\pm 3\%$) ^a
AAS method	32.3 mg ($\pm 5\%$)
ICP-AES method	34.3 mg ($\pm 5\%$)
Calibration source	Amersham Standard Solution
Disintegration rate	2.86 dpm ($\pm 5\%$) ^b
Specific activity	0.0893 dpm/mg of Co ($\pm 6\%$) ^c

^a Each measurement was assigned a weight proportional to the reciprocal of the square of its estimated standard deviation.

^b Value corrected for decay during the 10.3-day count started on November 21, 1988.

^c Value normalized arbitrarily to August 6, 1988.

Table 12. Values from recent American and Japanese studies of the specific activities of cobalt in steel samples from Hiroshima.

Sample description	Study	Specific activity ^a (dpm/mg of Co)
Handrail from stack	American ^b	$(2.54 \pm 0.15) \times 10^{+1}$
	Japanese ^c	$(2.64 \pm 0.38) \times 10^{+1}$
D-plate from bridge	American ^b	$(3.36 \pm 0.30) \times 10^{-1}$
	Japanese ^c	$(3.09 \pm 0.48) \times 10^{-1}$
C-plate from bridge	American ^b	$(1.54 \pm 0.15) \times 10^{-1}$

^aValues extrapolated back to the time of bombing on August 6, 1945.

^bThis work as recently reported by Kerr et al (1989).

^cJapanese studies as recently reported by Kimura et al (1989).

that the thermal neutron flux at the surface of the earth is about $1.5 \times 10^{-3} \text{ n cm}^{-2} \text{ s}^{-1}$, and the equilibrium background activation from cosmic-ray neutrons is roughly $3.5 \times 10^{-5} \text{ dpm per mg of Co}$. Two different steel samples were counted to establish the background rates for the cobalt-60 measurements at PNL (Table 9). One of the samples was obtained from a deep underground mine, and the other from a light steel-frame building. The latter sample was exposed to cosmic-ray neutrons, and the former sample was not. The expected difference in the background rates based on calculation for the above-ground sample from the light steel-frame building was $0.0003 \text{ cpm} [(3.5 \times 10^{-5} \text{ dpm per mg of Co}) (49 \text{ mg of Co per kg of steel}) (4.108 \text{ kg of steel}) (0.0399 \text{ count per disintegration})]$. Both samples were counted on Detector System 9 at PNL, and the measured difference was 0.0002 cpm (Table 9). Thus, the background activation from cosmic-ray neutrons was small compared to the standard deviations of the cobalt-60 measurements (Tables 10 and 11) and the specific activity of the handrail and bridge samples can still be attributed mainly to the nuclear explosion on August 6, 1945 (Table 12).

COBALT-60 CALCULATIONS

The effect of a sample's environment on cobalt activation within the sample was determined by the use of adjoint neutron-transport calculations (Cramer, 1985). The adjoint neutron fluence was then folded with neutron fluences from forward-mode calculations with the DOT-4 code (Rhoades and Childs, 1982). These forward-mode calculations follow the neutrons as they were transported from the source toward the detector (i.e., from the bomb toward the steel sample). An adjoint-mode calculation follows the transport from the steel sample (i.e., the

adjoint source) toward the bomb (i.e., the adjoint detector). Proper folding of the forward and adjoint fluences at a coupling surface between the forward source (the bomb) and adjoint source (the steel sample) will produce the desired response (i.e., cobalt activation in the steel sample by neutrons from the bomb).

The VISTA code (Rhoades, 1988) was used to extract the directional neutron fluences from the previous forward-mode calculations with the DOT-4 code (Kerr et al, 1987). Folding of the inward-directional, forward-mode fluences with the outward-directional, adjoint-mode fluences was accomplished using an updated and modified version of the well-known MORSE Monte Carlo transport code (Emmett, 1975; Cramer and Slater, 1989). This modified MORSE code uses linear interpolation to obtain the forward-mode fluences at the appropriate ground ranges (687 m for the handrail sample and 1295 m for the bridge sample) and at various distance intervals both above and below ground (-0.5 to 0 m, 0 to 2 m, 2 to 6 m, 6 to 12 m, 12 to 18 m, 18 to 25 m, 25 to 50 m, and 50 to 75 m). The 62.5-m midpoint of the latter interval was used as the upper boundary for a parallelepiped coupling surface between the forward and adjoint sources.

The adjoint fluence calculations were performed using the MORSE code as modified by Cramer and Slater (1989) and the cross sections for cobalt activation in the steel samples as the adjoint source (Cramer, 1985). These MORSE-code calculations also required input on the cross sections for neutron interactions with air, ground, concrete, steel, water, and asphalt. Grouped cross-section sets for air and ground were available from the previous forward-mode calculations with the DOT-4 code (Kerr et al, 1987). Additional sets were constructed using the

forward-mode fluences at the appropriate ground ranges (687 and 1295 m), the AMPX modular-code system (Greene et al, 1978), and the material number densities in Table 13 (1 barn equals $1 \times 10^{-24} \text{ cm}^2$). The specific features of each sample and its immediate surroundings were modeled within a large parallelepiped as follows.

Chugoku Electric Company: A mathematical model of the building and smokestack was placed in a rectangular parallelepiped that extended -20 and +14 m in the x-direction, -9.8 and +29.5 m in the y-direction, and -0.5 and +62.5 m in the z-direction. The origin of the coordinate system was centered in the base of the smokestack, the x-axis was perpendicular to the wall behind the smokestack, the y-axis was parallel to the same wall, and the z-axis was perpendicular to the ground (Figure 30). To properly orient the model with respect to the hypocenter, the x-axis was rotated 24 degrees in a clockwise direction from a line connecting the origin of the coordinate system and the hypocenter (Figure 5). After the rotation, the positive x-axis was pointed in a northerly direction and the positive y-axis was pointed in a westerly direction (Figure 13). The origin of the coordinate system was located at a distance of 687 m from the hypocenter (Table 1).

Only the shell of the building was modeled (Figure 13). Any neutrons which penetrated the outside shell were absorbed inside the building. The thicknesses of the concrete and plaster in the outer walls and roof were assumed to be 38.1 and 25.4 cm, respectively (Joint Commission 1951, Vol. 6, pp. 149-152 and pp. 187-188). The section of handrail that was modeled is shown in Figure 15. The curvature of the top rod and the bottom plate was eliminated by modeling them as a

Table 13. Material number densities (atoms barn⁻¹ cm⁻¹).

Element	Concrete ^a	Steel ^b	Water ^c	Asphalt ^d
Hydrogen	7.695E-3		6.670E-2	2.808E-3
Lithium-6	9.130E-7			
Lithium-7	1.130E-5			
Beryllium	2.460E-7			
Boron-10	5.120E-7			
Boron-11	2.050E-6			
Carbon	9.920E-4	3.310E-4		4.006E-3
Nitrogen	9.890E-6			1.620E-4
Oxygen	4.787E-2		3.340E-2	3.167E-2
Sodium	1.096E-3			1.403E-3
Magnesium	2.620E-4			8.848E-4
Aluminum	3.244E-3			3.189E-3
Silicon	1.381E-2	8.089E-5		1.072E-2
Phosphorus	1.120E-5			
Sulfur				7.060E-5
Potassium				8.252E-4
Calcium	1.655E-3			1.073E-3
Titanium	4.340E-5			
Vanadium	8.430E-7			
Chromium	9.060E-7			
Manganese	1.130E-5	3.171E-4		
Iron	4.020E-4	8.394E-2		9.630E-4
Cobalt	9.400E-8	1.839E-5		
Nickel	8.730E-8	2.177E-5		
Copper	4.800E-7	2.980E-4		
Zirconium	8.350E-7			
Cadmium	2.090E-8	2.106E-6		
Barium	4.240E-6	1.172E-6		
Lead	1.670E-7			

^aBased on a mass density of 2.3 g cm⁻³ from the report by the Joint Commission (1951, Vol. 6, pp. 149-152) and the mass fractions in Table 7 of this report for the coarse aggregate.

^bBased on a mass density for steel of 7.86 g cm⁻³ (Lindsay, 1963, p. 24, also see mass density for iron on p. 20) and the mass fractions in Table 6 of this report for the bridge samples.

^cBased on a mass density for water of 0.9982 g cm⁻³ at 20°C (Lindsay, 1963, pp. 147).

^dBased on average of 1.88 g cm⁻³ (range of 1.76 to 2.00 g cm⁻³) for the mass density of the asphalt mixture from Crim (1988). The mass fractions for the elements in asphalt and amount of asphalt in the mixture were obtained from Wantland (1988). Asphalt was 5% of the mixture by mass, and 95% was aggregate. The mass fractions for the elements in the aggregate were taken from the CRC Handbook (1963, p. 3486, see table on common elements in the earth's crust).

Figure 30. Schematic of the Chugoku Electric Company showing coordinate system used in the MORSE Monte Carlo calculations.

right circular cylinder and a rectangular parallelepiped, respectively (Table 2). The handrail sample was approximately 0.5 m from the outer surface of the stack (Fujita, 1988) and 25 m above ground (Joint Commission, 1951, Vol. 6, Figure 28, p. 189; Oughterson and Warren, 1956, Figure 3.39, p. 60). The ground thickness in the negative z-direction was 0.5 m.

Yokogawa Bridge: A total of six large samples were cut from the Yokogawa Bridge (Figure 31). First, a top section of the arch on the east side of the bridge was divided equally and the portion facing toward the west was scrapped. Next, six samples were cut from the portion facing to the east as shown in Figure 31 (Fujita, 1988). Finally, samples 1 and 4 were made available for study in the United States, samples 2 and 5 were held in reserve by RERF, and samples 3 and 6 were made available for study in Japan. Sample 3 was used in the study by Kimura et al (1989) and sample 4 was used in this study (Table 12).

A model of both the river and the bridge was placed in a rectangular parallelepiped that extended ± 30 m in the x-direction, ± 40 m in the y-direction, and -4.63 and $+62.5$ m in the z-direction. The origin of the coordinate system was located on the deck at the center of the bridge, the x-axis was perpendicular to the flow of traffic on the bridge, the y-axis was parallel to the flow of traffic, and the z-axis was perpendicular to the deck (and the ground). The surface of the river was located at 4.13 m in the negative z-direction (Shigematsu, 1985), and for calculational purposes, the depth of the river was 0.5 m. The width of the river was 61.0 m (± 30.5 m in the y-direction) and it extended to the surfaces of the parallelepiped in the x-direction

Figure 31. Schematic showing orientation of six steel samples from top of arch on the east side of the Yokogawa Bridge.

(± 30 m). To properly orient the model with respect to the hypocenter, the x-axis was rotated 60 degrees in a counterclockwise direction from a line connecting the origin of the coordinate system and the hypocenter (Figure 5). After the rotation, the positive x-axis was pointed in an easterly direction and the positive y-axis was pointed in a northerly direction. The origin of the coordinate was located at a distance of 1295 m from the hypocenter (Table 1).

The deck of the bridge was modeled as a 20-cm (8.0-inch) thick concrete pad with a wearing surface of 3.8-cm (1.5-inch) thick asphalt (Crim 1988). These surfaces were 7.16 m (23.5 feet) in width and 61.0 m (200 feet) in length (Table 3 and Figure 21). The entire steel support structure of the bridge was not modeled. It was felt that only the steel surrounding the samples would affect the cobalt-60 calculations. In addition, modeling of the entire steel support structure would require greater running time for the MORSE code, with few benefits. Hence, modeling was limited to the steel arch on the east side of the bridge (Figure 20) and to a 1.5-m (5.0-foot) section at the top of the arch from which the samples were cut (Fujita, 1988). This section was modeled as a rectangular parallelepiped whose ends were capped with 2.54-cm (1.00-inch) steel plates to account for the downward concaveness of the steel structure (Figures 20 and 21).

Calculational Results: Table 14 presents the results of the cobalt-60 calculations for the handrail and bridge samples, assuming a bomb yield of 15 kt (Malik et al, 1987). The adjoint-MORSE calculations were made using several different building and bridge configurations to better understand what materials were important to the final values.

Table 14. Summary of data from ORNL calculations of the specific activity of cobalt in the handrail and bridge samples, assuming a bomb yield of 15 kt.

Calculation	Location of adjoint source	Specific activity (dpm/mg of Co)		
		C-plate	D-plate	Handrail
#1	In air at elevation over ground ^a	2.03E-1	2.03E-1	2.71E+1
#2	In air at elevation over river ^b	1.82E-1	1.82E-1	
#3	In C-plate only, no other steel ^c	1.52E-1		
#4	In C- and D-plates, no other steel ^c	1.25E-1	1.34E-1	
#5	In sample pieces with full modeling ^d	9.42E-2	1.24E-1	2.45E+1
#6	In sample pieces of Japanese study ^e		1.17E-1	2.45E+1

^aThe elevations were 10 m for the samples from the Yokogawa Bridge (C- and D-plates) and 25 m for the sample from the smokestack of the Chugoku Electric Company (handrail).

^bWidth of river was 61 m and water was 4.13 m beneath the floor of the bridge (the bridge floor was included in the calculation).

^cIncluded the river and floor of bridge, but the calculation excluded the effect of any additional shielding of the C- or D-plates by other steel in the bridge support (Figure 31).

^dIncluded the river, floor, and steel arch on the east side of bridge (and the handrail, smokestack, and exterior shell of the Chugoku Electric Company Building).

^eSample 3 from the bridge was used in the study by Kimura et al (1988) and sample 4 from the bridge was used in this study (Figure 31). The D-plate of sample 4 faced downward toward the river, and the D-plate of sample 3 faced upward toward the sky.

Calculation 1 was a free-field calculation with the adjoint source located in the volumes of the handrail and bridge samples that were counted at PNL (Table 9, Figures 28 and 29). No steel, concrete, asphalt, or water was included in the calculations. The only materials were air and ground. The sample volumes and the positive z-portions of the parallelepipeds were filled with air, and the ground was modeled as a flat surface in the negative z-portions of the parallelepipeds. This configuration duplicated the simple air-over-ground geometry used in the forward-mode calculations with the DOT-4 code (Kerr et al, 1987).

Calculation 2 was also a free-field calculation with the adjoint source located in the volumes of the bridge samples that were counted at PNL. There was no steel in the C- and D-plates or in the bridge structure, but the river and floor of the bridge were included in the calculation. The results show the combined effects of the bridge floor (the concrete and asphalt) and river (the air and water beneath the bridge) on cobalt activation in the C- and D-plates.

Calculation 3 was the same as calculation 2 except the C-plate was steel. The result shows the effect of self-shielding on cobalt activation within the C-plate (or the D-plate). Calculation 4 was also the same as calculation 2 except the C- and D-plates were both steel. These results show the effect of mutual-shielding on cobalt activation within the C- and D-plates. It needs to be noted that the combined effects of self-shielding and mutual-shielding had a significant impact on cobalt-activation within the C- and D-plates (Table 14).

Calculation 5 used the full models for the samples and their immediate surroundings as discussed previously. These models included the river, bridge floor, and steel arch on the east side of the Yokogawa

Bridge, and the handrail, smokestack and exterior shell of the Chugoku Electric Company. A comparison of results from calculations 1 and 5 shows that the use of the full model for the handrail sample only decreased the cobalt activation by about 10%. However, the full model for the bridge samples was found to decrease the cobalt activation by approximately a factor of two in both the C- and D-plates (Table 14).

Calculation 6 is the same as calculation 5 except the D-plate was part of sample 3 from the bridge (Figure 31). Sample 3 was used in the Japanese study by Kimura et al (1989) and sample 4 was used in this study (Figure 21). The D-plate of sample 4 faced downward toward the river, while the D-plate of sample 3 faced upward toward the sky. The cobalt activation in the D-plate of sample 3 is slightly less than that in the D-plate of sample 4 because the earth beneath the samples (ground and water) is a better neutron moderator than the air above the samples (atmospheric gases and water vapor).

DISCUSSION

Table 15 provides a summary of the calculated to measured ratios for the cobalt activation in the handrail and bridge samples. The ratios for the bridge sample can be compared directly with other ratios in Figure 10. It needs to be noted that the rebar data suggested a discrepancy of about 4 between calculated and measured values at a ground range of 1198 m, while the newer bridge data suggests a smaller discrepancy of approximately 2 between calculated and measured values at a ground range of 1295 m.

The ratios for the handrail sample cannot be compared directly with the other ratios in Figure 10. Because of differences in height of the

Table 15. Summary of data from recent American and Japanese studies of the specific activity of cobalt in steel samples from Hiroshima.

Sample description	Ground range (m)	Specific activity (dpm/mg of Co)		
		Calculated	Measured	Ratio
Handrail from stack	687 ^a	2.45E+1 ^b	2.54E+1 ^c	0.965
		2.45E+1 ^b	2.64E+1 ^d	0.928
D-plate from bridge	1295 ^a	1.24E-1 ^b	3.36E-1 ^c	0.369
		1.17E-1 ^b	3.09E-1 ^d	0.379
C-plate from bridge	1295 ^a	9.42E-2 ^b	1.54E-1 ^c	0.612

^aSee Figure 5 and Table 1 of this report.

^bSee Table 14 of this report.

^cSee Table 12 of this report and Kerr et al (1989).

^dSee Table 12 of this report and Kimura et al (1989).

various samples, particularly those at the smaller ground ranges, the calculated to measured ratios must be compared using either slant ranges or scaled ground ranges (Table 16). The scaled ground range places the individual samples at the appropriate slant ranges, but it treats the samples as if they were all located at ground level (Figure 32). The scaled ground range is equal to the square root of $R^2 + h^2 - 2hH$, and the slant range is equal to the square root of $S^2 + H^2$, where S is the scaled ground range, R is the actual ground range, h is the height of the sample or its elevation over ground, and H is the burst height of the bomb (Table 16).

The ratios for the rebar samples must be reexamined using the data for Hiroshima-type concrete in Table 8. A calculation and measurement for the rebar from the Chugoku Electric Company would be helpful in establishing the precision of the ratios for other rebar samples (Maruyama and Kawamura, 1987). The measurements for the handrail and D-plate are well-established due to the independent Japanese study by Kimura et al (Table 12). An independent Japanese measurement of the cobalt-60 in the C-plate would also be helpful in resolving the current discrepancy of about 2 between measurements and calculations for the bridge sample. However, the ultimate resolution to the problem will require an updated source-term calculation for the Hiroshima bomb (Whalen, 1987) and a more detailed analysis of the uncertainties in the atmospheric neutron-transport calculations for Hiroshima bomb-type sources (Kerr et al, 1987).

Table 16. Ratios of calculated to measured values for activation of cobalt in Hiroshima.

Sample location ^a	No.	Description	Height (m)	Ground range (m)		Specific activity (dpm/mg of Co)		
				Actual	Scaled	Calculated	Measured	Ratio
Honkawa Primary School	2-1	Iron ring	16	373 ^b	348 ^c	3.79E+2 ^d	2.63E+2 ^e	1.44
Fukuromachi Primary School	2-2	Iron ring	12	441	425	2.40E+2	1.98E+2	1.21
Kirin Beer Hall	2-3	Iron ring	14	650	638	5.09E+1	5.89E+1	0.864
Kodokan Building	2-4	Iron ring	14	727	716	3.00E+1	3.20E+1	0.938
Hiroshima City Hall	2-5	Iron ring	12	997	990	3.20E+0	6.88E+0	0.465
Yokogawa Bridge	3-1	C-plate	10	1295 ^f	1290 ^c	9.42E-2 ^f	1.54E-1 ^f	0.612
		D-plate	10	1295	1290	1.24E-1	3.36E-1	0.369
		D-plate	10	1295	1290	1.17E-1	3.09E-1	0.379
Chugoku Electric Company	3-2	Handrail	25	687 ^f	666 ^c	2.45E+1 ^f	2.54E+1 ^f	0.965
		Handrail	25	687	666	2.45E+1	2.64E+1	0.928

^aSee Figure 5 of this report.

^bSee Table 2 of Hashizume (1983).

^cScaled ground range is equal to the square root of $R^2 + h^2 - 2hH$, where R is the actual ground range, h is the height of the sample or its elevation over ground, and H is the burst height of the bomb (580 m).

^dObtained using linear interpolation between values in Table 9 of Mendelsohn (1987) and a bomb yield of 15 kt from Table 4 of Malik et al (1987).

^eObtained using the values from Table 2 of Hashizume (1983), a counter efficiency of 12% or one beta particle count per 8.33 disintegrations of cobalt-60 (Hashizume et al, 1967), and a factor of 12.9 to extrapolate the specific activities back to the time of bombing on August 6, 1945 (Hashizume et al, 1967).

^fSee Tables 1 and 15 of this report.

Figure 32. Calculated to measured ratios for cobalt activation in Hiroshima, using data from studies at Lawrence Livermore National Laboratory (LLNL), Japanese National Institute of Radiological Sciences (NIRS), Japan Chemical Analysis Center (JCAC), and Oak Ridge National Laboratory (ORNL).

ACKNOWLEDGEMENTS

The authors wish to thank the following individuals who in some instances provided assistance during the study and in other instances provided constructive criticism used in the preparation of this report.

C. W. Alexander, Oak Ridge National Laboratory, Oak Ridge, TN
J. Crim, BMC Corporation, Seattle, WA
R. F. Christy, California Institute of Technology, Pasadena, CA
J. K. Dickens, Oak Ridge National Laboratory, Oak Ridge, TN
K. F. Eckerman, Oak Ridge National Laboratory, Oak Ridge, TN
J. S. Eldridge, Oak Ridge National Laboratory, Oak Ridge, TN
W. H. Ellett, National Research Council-National Academy of Sciences, Washington, DC
N. M. Ferguson, Oak Ridge National Laboratory, Oak Ridge, TN
S. Fujita, Radiation Effects Research Foundation, Hiroshima, Japan
F. Hajnal, Environmental Measurements Laboratory, New York, NY
G. L. Herndon, Paducah Gaseous Diffusion Plant, Paducah, KY
J. M. Keller, Oak Ridge National Laboratory, Oak Ridge, TN
R. M. Lindstrom, National Institute for Standard and Technology, Gaithersburg, MD
E. Mendelsohn, Lawrence Livermore National Laboratory, Livermore, CA
J. H. Reeves, Pacific Northwest Laboratories, Richland, WA
C. O. Slater, Oak Ridge National Laboratory, Oak Ridge, TN
M. R. Smith, Pacific Northwest Laboratories, Richland, WA
B. R. Stone, C. Reed Davis Contractors, Inc., Concord, TN
D. F. Wantland, West Hollow Research Center, Houston, TX
T. Watanabe, Radiation Effects Research Foundation, Hiroshima, Japan
R. M. Young, Defense Nuclear Agency, Alexandria, VA

This work was funded by the U.S. Defense Nuclear Agency under contract DNA 88-853 with Martin Marietta Energy Systems, Inc., and interagency agreement DOE-0046-A130-A1 with the U.S. Department of Energy.

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