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TITLE: GAMMA-RAY SPECTRA AND DOSES FROM THE LITTLE BOY REPLICA

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ABSTRACT

Most of our radiation safety guidelines in the nuclear industry are based on the data concerning the survivors of the nuclear explosions at Hiroshima and Nagasaki. Crucial to determining these guidelines is the radiation from the explosions. We have measured gamma-ray pulse-height distributions from an accurate replica of the Little Boy device used at Hiroshima, operated at low power levels near critical. The device was placed outdoors on a stand 4 m from the ground to minimize environmental effects. The power levels were based on a monitor detector calibrated very carefully in independent experiments. High-resolution pulse-height distributions were acquired with a germanium detector to identify the lines and to obtain line intensities. The 7631-7645 keV doublet from neutron capture in the heavy steel case was dominant. Low-resolution pulse-height distributions were acquired with bismuth-germanate detectors. We calculated flux spectra from these distributions using accurately measured detector response functions and efficiency curves. We then calculated dose-rate spectra from the flux spectra using a flux-to-dose-rate conversion procedure. The integral of each dose-rate spectrum gave an integral dose rate. The integral doses at 2 m ranged from 0.46 to 1.03 mrem per 10^{13} fissions. The output of the Little Boy replica can be calculated with Monte Carlo codes. Comparison of our experimental spectra, line intensities, and integral doses can be used to verify these calculations at low power levels and give increased confidence to the calculated values from the explosion at Hiroshima. These calculations then can be used to establish better radiation safety guidelines.

INTRODUCTION

Most of our radiation safety guidelines in the nuclear industry are based on the data concerning the survivors of the nuclear explosions at Hiroshima and Nagasaki. Crucial to determining these guidelines is the radiation output of the explosions. For many years we have believed that the output from the Nagasaki explosion was well determined but that the output from the Hiroshima explosion was less certain.

As part of a recent effort to more accurately determine the output at Hiroshima, we have measured the gamma-ray pulse-height distributions from a replica of the Hiroshima device operating at accurately known power levels near critical. We measured high-resolution distributions to determine gamma-ray line intensities. We measured low-resolution distributions which we then converted to flux distributions, dose-rate distributions, and integral doses using a computer code developed at Los Alamos.

EQUIPMENT AND METHODS

Our equipment and methods are discussed in detail elsewhere (Moss et al. 1984a; Moss, Tisinger, and Hamm, 1984b; Moss, Lucas, Tisinger, and Hamm, 1984c). We present here only a brief review supplemented with some new information.

Our detector for the high-resolution measurements is a high-purity germanium detector with an efficiency of 21% relative to a 7.62-cm-diameter by 7.62-cm-long NaI(Tl) detector at 1332 keV. The resolution is 1.8 keV (full width at half maximum) at 1332 keV. The detector has an all-attitude dewar for liquid nitrogen that facilitates positioning.

We calibrated the germanium detector efficiency as a function of energy from 60 to 10829 keV using radioactive sources and a (n,γ) reaction. The gamma-ray "point" sources used were ^{241}Am, ^{57}Co, ^{203}Hg, ^{133}Ba, ^{137}Cs, ^{54}Mn, ^{88}Y, ^{60}Co, ^{22}Na, ^{208}Tl, ^{166m}Ho, and a mixed source containing ^{125}Sb, ^{154}Eu, and ^{155}Eu from the US National Bureau of Standards. The reaction used was ^{14}N(n,γ)^{15}N, which produces gamma rays up to an energy of 10829 keV.

Our detector for the low-resolution measurements is a bismuth-germanate (BGO) scintillator 7.62 cm in diameter by 7.62 cm long. Because its resolution is 14.6% (full width at half maximum), simple spectra are required for calibration of the efficiency and response functions. The gamma-ray point sources used were ^{57}Co, ^{139}Ce, ^{203}Hg, ^{113}Sn, ^{51}Cr, ^{7}Be, ^{85}Sr, ^{137}Cs, ^{54}Mn, ^{88}Y, ^{65}Zn, ^{22}Na, ^{60}Co, and ^{208}Tl. The reactions used were the ^{9}Be(α,n)^{12}C reaction in a plutonium-beryllium source and the ^{14}N(p,γ)^{15}O reaction produced in a Van de Graaff target. The ^{9}Be(α,n)^{12}C reaction produces a 4439-keV gamma ray; the ^{14}N(p,γ)^{15}O produces a 8284-keV gamma ray at the 1058-keV proton energy resonance.

We have also used a ^{16}N source that produces a 6129-keV gamma ray. The only significant interference is a weak (7%) 7115-keV gamma ray. Because the half-life is only 7 s, ^{16}N must be continuously produced. We used the reaction ^{16}O(n,p)^{16}N in the cooling water of a reactor to produce the ^{16}N. Water was pumped through a thin wall of an aluminum chamber (Figure 1) to serve as our ^{16}N source. The intensity of the 6129-keV gamma ray was monitored with a calibrated germanium detector. While this energy is below the 7645-keV line from the Little Boy device, it is close enough to provide a good calibration. This energy might be useful for calibrating other detectors such as Geiger-Müller tubes and ionization chambers. Traditionally, the highest energy at which these instruments have been calibrated is 1332 keV (^{60}Co). Since the response is known to be energy dependent (Thompson, 1978; Plassmann, Pederson, and Moss, 1984), a calibration point at a higher energy is very desirable.

Our procedure for the low-resolution measurements was to acquire pulse-height distributions with the bismuth-germanate detector. A code called GPEEL, which runs on a Control Data Corporation (CDC) 7600 computer or a Cray computer, uses the measured detector efficiencies (Moss, Tisinger, and Hamm, 1984b) and response functions in a stripping procedure (Moss et al., 1984a) to calculate the gamma-ray flux in photons/cm^2/s as a function of energy from the raw BGO pulse-height distributions. The code then converts the resulting flux distribution to a dose-rate distribution using a flux-to-dose-rate curve (Figure 2), based on the work of Dimbylow and Francis (1979). The integral over this dose-rate distribution is the total gamma-ray dose rate.

For the BGO measurements and some of the germanium measurements the Little Boy replica was supported outdoors on a stand (Figure 3); the

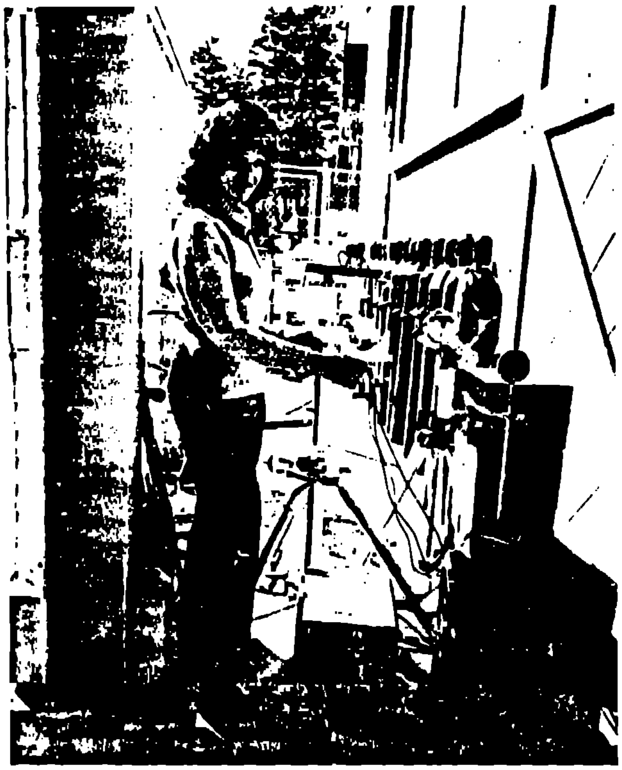

Figure 1. ^{16}N setup at reactor.

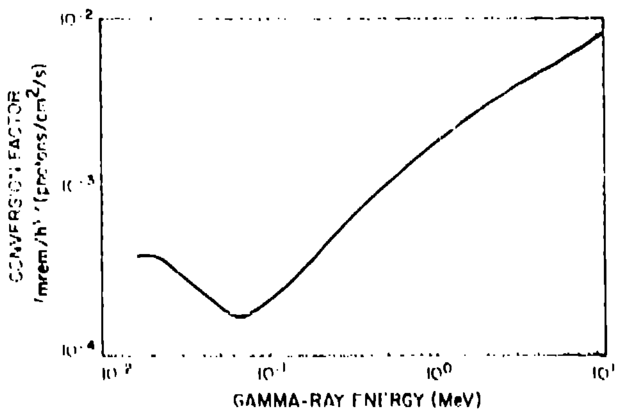

Figure 2. Gamma-ray flux-to-dose-rate curve based on the work of Dimbylow and Francis.

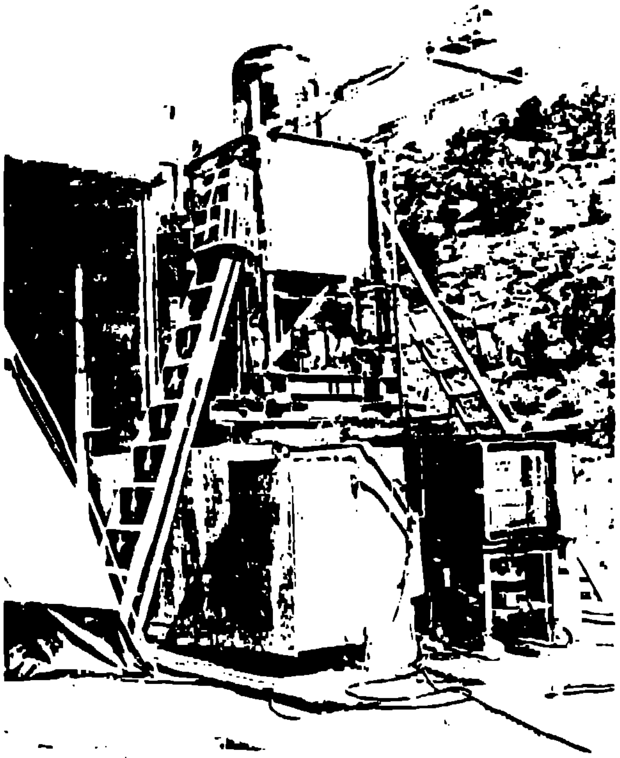

Figure 3. The Little Boy replica on a stand outdoors. The detector on the arm extending out from the replica at 90° is the high-purity germanium detector in an all-attitude dewar. The arm can be rotated up to 0°. Two monitor detectors can be seen. One is to the left of the Little Boy replica; the second is on the lower right side of the stand.

geometrical center of the core of the device when operating was 4.0 m from the ground. For the rest of the germanium measurements the Little Boy replica and stand were located in a concrete building. We believe that the intensities of gamma-ray lines that could be uniquely associated with Little Boy were not changed significantly by the building from what they were outside. However, scattering did change the continuum.

RESULTS

We identified the gamma-ray lines from Little Boy from a high-resolution distribution (Figure 4) acquired with the high-purity germanium detector. Table 1 lists the identifications and intensities corrected for detector efficiency for some of the most significant gamma-ray lines. The intensity given in the third column is really an "apparent source strength" obtained by multiplying the observed flux in photons/cm^2/s at the detector position by 4π times the square of the distance to the center of the core. The normalized intensity given in the fourth column is obtained by dividing the value in the third column by the number of fissions. As expected, the lines from $Fe(n,\gamma)$ are dominant, especially the 7645- and 7631-keV lines. The lines from ^{234m}Pa (which is a daughter of ^{238}U) are present but are only moderately strong because of the shielding provided by the massive steel case. Similarly the fission product lines are weak and only the those from ^{140}La can be easily identified. The $Si(n,\gamma)$ and $H(n,\gamma)$ lines are believed to come from the soil and concrete.

Results at (0°, 2 m) and 90°, 0.75 m) are shown in Figures 5 and 6, respectively. Zero degrees is along the cylindrical axis at the rounded end of the replica and 90° is the horizontal plane. The distances are measured from the center of the core. In each figure the binned pulse-height distribution, flux distribution, and dose-rate

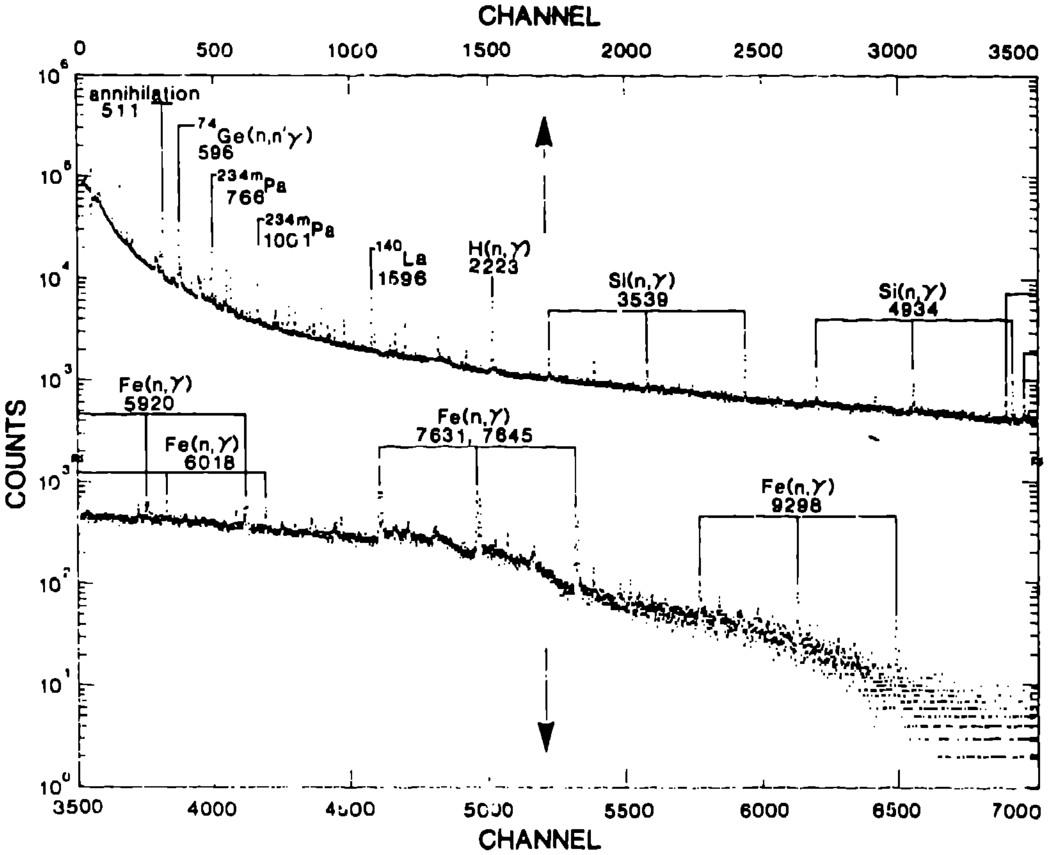

Figure 4. High-resolution pulse-height distribution measured at (90°, 2 m). The acquisition live time was 3000 sec and the number of fissions was 1.81 x 10^{12}. The major peaks are labeled with the radioactive nuclide and the gamma-ray energy in keV.

distribution are shown. The 7.6-MeV peak from Fe(n,γ) is the most prominent feature. The integral of the dose-rate distribution over energy is the total gamma-ray dose rate.

The integral doses up to 11 MeV at various positions around Little Boy, normalized to the number of fissions, are presented in Figure 7 and listed in Table 2. The number of fissions is based on the monitor detectors that H. M. Forehand and G. E. Hansen of Los Alamos National Laboratory calibrated in independent experiments. In previous work on sources that produced negligible gamma-ray intensity above 5 MeV, we assigned a total uncertainty of ±7% to our results. In the present work, the spectra extend well above 5 MeV where the BGO detector efficiency and response functions are not as well quantified. We therefore assign a total uncertainty of ±15% to our present results. The dip at (30°, 0.75 m) corresponds to the maximum diagonal thickness of steel.

TABLE 1. Gamma-Ray Line Intensities

Gamma-Ray Energy (keV)	Nuclide or Reaction	Intensity x 10^{-6} (photons/s)	Normalized Intensity x 10^{7} (photons/s/fission)
662	^{137}Cs	0.37	2.02
766	$^{234m}Pa(^{238}U)$	1.31	7.23
846	$Fe(n,n'\gamma)$	0.76	4.21
1001	$^{234m}Pa(^{238}U)$	2.05	11.31
1173	^{60}Co	0.40	2.23
1332	^{60}Co	0.46	2.57
1596	^{140}La	1.09	6.03
2223	$H(n,\gamma)$	1.76	9.70
2754	^{24}Na	0.40	2.21
3539	$Si(n,\gamma)$	0.96	5.33
4934	$Si(n,\gamma)$	0.98	5.44
5920	$Fe(n,\gamma)$	0.38	2.07
6018	$Fe(n,\gamma)$	0.44	2.44
6419	$Ca(n,\gamma)$	0.41	2.24
7631	$Fe(n,\gamma)$	1.23	6.81
7645	$Fe(n,\gamma)$	1.13	6.23
9298	$Fe(n,\gamma)$	0.16	0.88

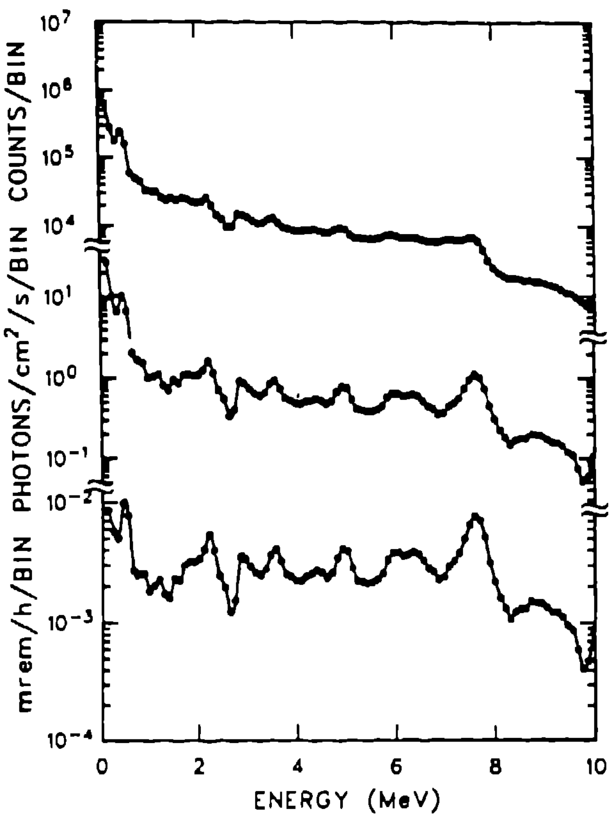

Figure 5. Binned pulse-height distribution (top), flux spectrum (middle), and dose-rate spectrum (bottom) at (0°, 2 m). The 7.6-MeV peak from Fe(n,γ) is the most prominent feature of the distribution.

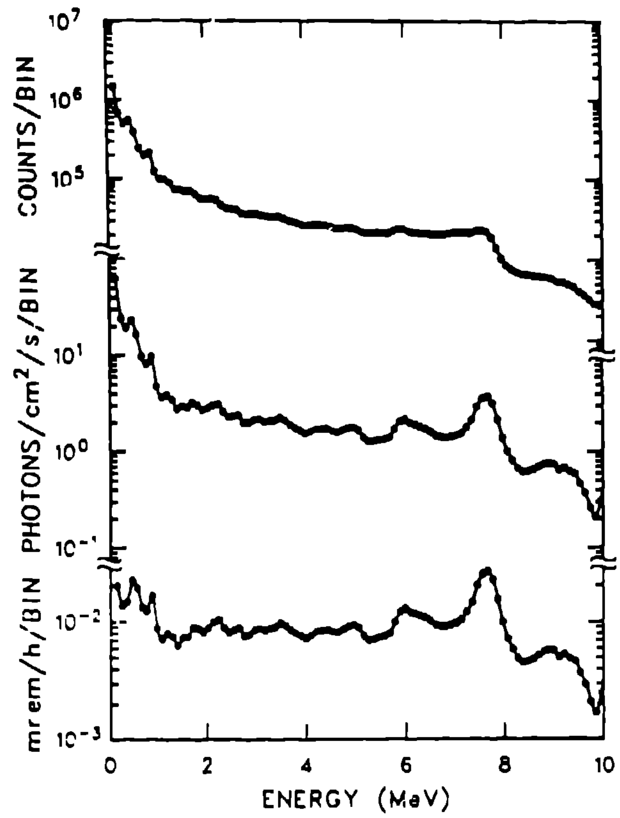

Figure 6. Binned pulse-height distribution (top), flux spectrum (middle), and dose-rate spectrum (bottom) at (90°, 0.75 m). Again, the 7.6-MeV peak is the most prominent.

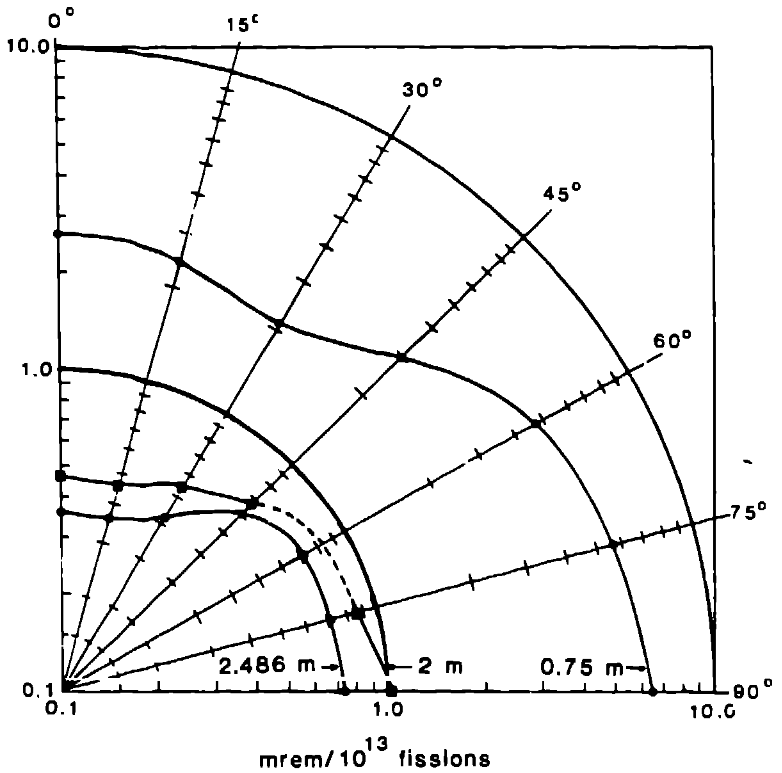

Figure 7. Log polar plot of the gamma-ray dose rates up to 11 MeV around the Little Boy replica normalized to the number of fissions. The dip at (30°, 0.75 m) corresponds to the maximum diagonal thickness of the steel case. (The dashed line represents inconclusive data.)

TABLE 2. Normalized Doses at Positions Around the Little Boy Replica[a]

Angle from Vertical (°)	Dose (mrem/10^{13} fissions) at Distance to Source 2.486 m	2.0 m	0.75 m
0	0.358	0.462	2.65
15	0.354	0.452	2.40
30	0.413	0.544	2.05
45	0.500	0.665	2.96
60	0.623	---	4.62
75	0.704	0.865	5.62
90	0.749	1.03	6.58

[a]The uncertainties of all BGO values are ±15%.

CONCLUSIONS

We have presented some gamma-ray line intensities, flux spectra, dose spectra, and integral doses around the Little Boy replica. The output can be calculated with Monte Carlo codes. Our experimental values can be used to verify these calculations at low power levels and give increased confidence to the calculated values from the explosion at Hiroshima. These calculations then can be used to establish better radiation safety guidelines.

We are continuing to refine our measurements. The results indicate significant contributions from the environment and from fission and activation products for which corrections will be made. We expect that at close distances the environmental effects are less important. Since we see a large contribution from gamma rays with an energy greater than 5 MeV, better calibration of our detectors in this energy range is important. We have taken additional data, which we hope to report in the near future.

ACKNOWLEDGMENTS

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