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Sulfur Activation at the Little Boy-Comet Critical Assembly: A Replica of the Hiroshima Bomb

George D. Kerr
Juel F. Emery
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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03; Microfiche A01

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ORNL/TM-9439
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Health and Safety Research Division

SULFUR ACTIVATION AT THE LITTLE BOY-COMET CRITICAL ASSEMBLY: A REPLICA OF THE HIROSHIMA BOMB

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Manuscript completed: December 1984
Report published: April 1985

Prepared for the
Office of Health and Environmental Research
U.S. DEPARTMENT OF ENERGY
Washington, D. C. 20545

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

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CONTENTS

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ABSTRACT

Studies have been completed on the activation of sulfur by fast neutrons from the Little Boy-Comet Critical Assembly which replicates the general features of the Hiroshima bomb. The complex effects of the bomb's design and construction on leakage of sulfur-activation neutrons were investigated both experimentally and theoretically. Our sulfur-activation studies were performed as part of a larger program to provide benchmark data for testing of methods used in recent source-term calculations for the Hiroshima bomb. Source neutrons capable of activating sulfur play an important role in determining neutron doses in Hiroshima at a kilometer or more from the point of explosion.

INTRODUCTION

The energy yield of and radiation leakage from the Nagasaki bomb are considered to be known to an adequate accuracy from measurements made during several early test firings.[1-5] In contrast, the Hiroshima bomb was never tested, and the energy yield (i.e., total fissions) and radiation leakage (i.e., source terms for neutrons and gamma rays) have been inferred from indirect evidence and theoretical calculations. The first modern calculations of source terms for the Hiroshima and Nagasaki bombs were made in 1975 by Preeg.[6] His calculations were done using available computer codes at Los Alamos National Laboratory (LANL) and one-dimensional (spherical) models of the two bombs. A one-dimensional

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model is a good approximation for the Nagasaki bomb (code named Fat Man) which was a spherical plutonium-implosion device.[7] However, the Hiroshima bomb (code named Little Boy) was a radically different uranium gun-assembly device. Its design was two-dimensional (cylindrical) and the effects of its cylindrical construction were noted in 1945 Japanese measurements of the activation of sulfur in Hiroshima.[1-3] Studies at the Oak Ridge National Laboratory (ORNL) have indicated that there was a blind spot in the radiation leakage through the nose of the Hiroshima bomb and that the bomb was tilted about 15^{0} to the vertical at the time of explosion.[3,8]

Source terms for a two-dimensional model of the Hiroshima bomb were calculated in 1982 by Whalen and co-workers at LANL[9,10] and the Little Boy-Comet Critical Assembly was constructed to provide benchmark data for the testing of various calculational methods.[11,12] This replica of the Hiroshima bomb has been used to perform three different kinds of experiments: (a) critical separation experiments to establish an upper limit for the energy yield,[11,12] (b) radiation spectra and dose measurements for comparison with calculations,[13-25] and (c) phenomenological experiments involving exposures of sulfur,[26] blood samples,[27] and Japanese roof tiles.[28] Source neutrons capable of activating sulfur by the $^{32}S(n,p)^{32}P$ reaction play an important role in determining the neutron doses in Hiroshima at a kilometer or more from the point of the explosion.[29]

The source terms for one- and two-dimensional models of the Hiroshima bomb have also been calculated at Lawrence Livermore National Laboratory (LLNL). Currently, the LLNL and LANL calculations for the leakage of sulfur-activation neutrons differ by a factor of two.[11,12]

The major part of this discrepancy is due to differences in the energy yields of the source-term calculations, but 20% of the discrepancy results from choices involving cross-section sets and representations. The dynamic disassembly of the exploding bomb is not duplicated in the experiments with the Little Boy-Comet Critical Assembly. However, the critical separation experiments will allow the energy yields of the LANL and LLNL calculations to be brought together, and the various radiation measurements and phenomenological experiments will aid in the choice of the best cross-sections and cross-section representations for use in final source-term calculations for the Hiroshima bomb.[12]

LITTLE BOY-COMET CRITICAL ASSEMBLY

The Little Boy-Comet Critical Assembly features a highly enriched uranium core surrounded by non-fissile components from a Hiroshima-type bomb found in storage at Los Alamos.[11,12] These non-fissile components consisting primarily of steel were mounted in a nose-up position on the Comet Assembly Machine at the Los Alamos Critical Assembly Facility. The ^{235}U core used in the critical separation experiments was fabricated from original Hiroshima bomb drawings and specification sheets.[30,31] A smaller ^{235}U core, sufficient only for sustained operation as a low-power delayed-critical reactor, was used in the radiation spectra and dose measurements and the phenomenological experiments. Criticality and control of the reactor were achieved by means of a hydraulic lift and precision screw mechanism on the Comet Assembly Machine. The only changes made in the general features of the Hiroshima-type bomb were the shortening of the gun barrel and the use of dummy initiators. Shortening the gun barrel allowed a shorter stroke on the hydraulic ram and screw mechanism and contributed to the operational safety of the reactor. Use of the dummy initiators also contributed to operational safety and did not compromise the various experiments in any way.[12]

The Little Boy-Comet Critical Assembly is usually operated inside Kiva 2, one of three heavy concrete buildings located several hundred meters from the centralized control room and office building at the Los Alamos Critical Assembly Facility.[13] During operations as a delayed-critical reactor, the center of the core is about 231 cm above floor level in Kiva 2 and 31 cm above the stand on the Comet Assembly Machine.[20] The cylindrical steel shell surrounding the core is 71 cm in diameter and its top surface extends approximately 60 cm above the center of the core. Because of complications from room-scattering, the Little Boy-Comet Critical Assembly has also been operated in an open area outside Kiva 2.[12,13] An additional stand was used during outside operations so that the center of the core was elevated four meters above ground level to minimize ground-scattering at detector distances of two meters or less.

We have made sulfur-activation measurements using the Little Boy-Comet Critical Assembly both inside and outside Kiva 2. The reactor power levels were monitored primarily by a moderated and uncompensated BF_3 ion chamber having both analog (Brown recorder) and digital (current integrator) readouts. Our sulfur-activation data were normalized to total fissions in the core as determined by counts on the digital current integrator and power calibration data supplied by LANL.[32] The Little Boy-Comet Critical Assembly and the detector locations used in our measurements are shown schematically in Fig. 1.

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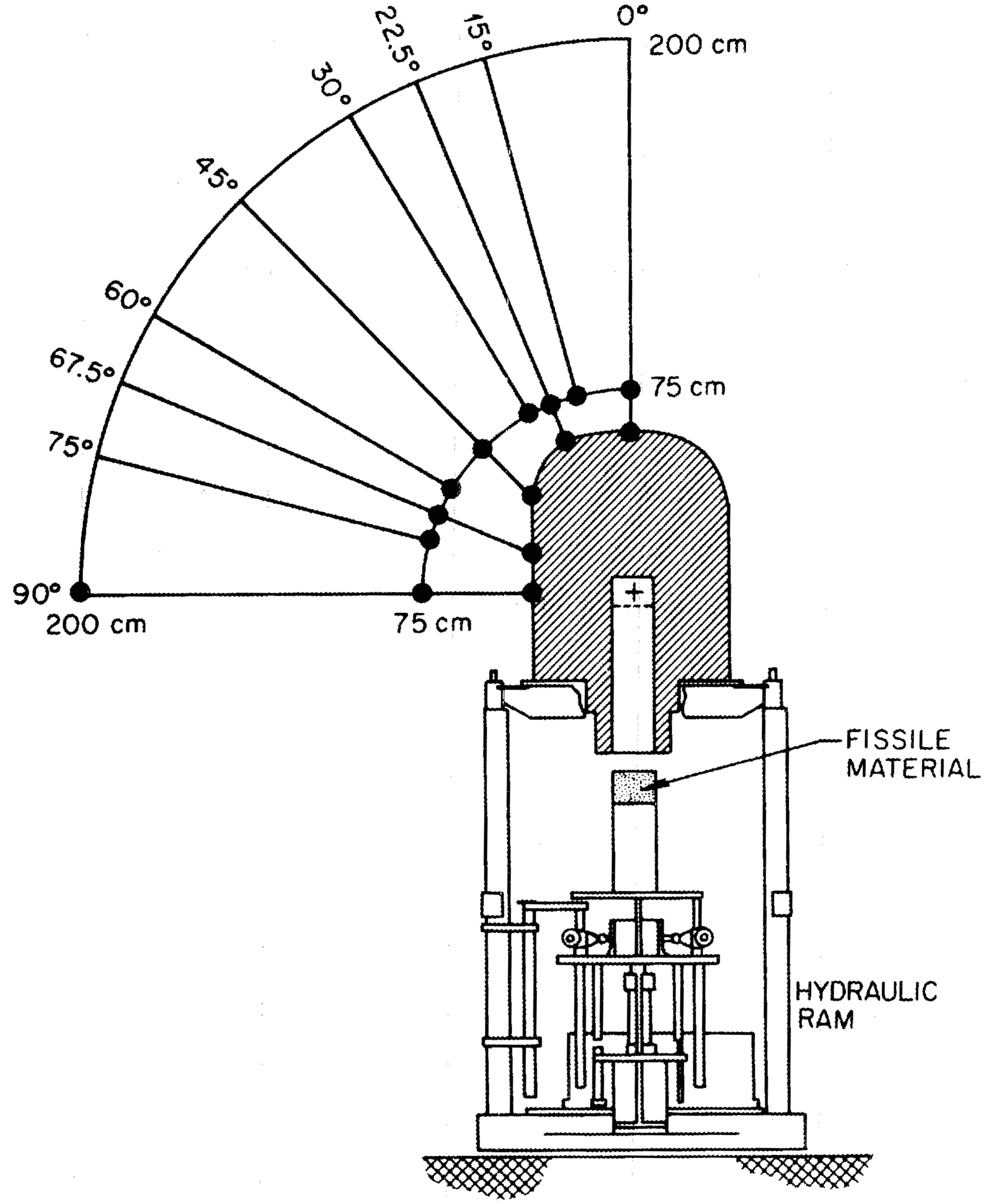

Figure 1. Detector locations (●) used in ORNL measurements of the activation of sulfur by fast neutrons from the Little Boy-Comet Critical Assembly.

SULFUR-ACTIVATION MEASUREMENTS

Our sulfur-activation measurements were made with high purity sulfur pellets having uniform diameters, thicknesses, and densities of 3.8 cm, 0.95 cm, and 2.0 g cm^{-3}, respectively. The ^{32}P formed by the $^{32}S(n,p)^{32}P$ reaction has a half-life of 14.3 days and decays by the emission of beta particles having a maximum energy of 1.71 MeV. The activated sulfur pellets were counted by placing the flat side exposed toward the reactor on the thin plastic scintillator of a beta spectrometer. To calibrate the beta spectrometer, we then measured the disintegration rate of the ^{32}P radioactivity in crushed and dissolved portions from several pellets using a calibrated liquid-scintillation counter. Due to the combined effects of background in the liquid scintillator and low ^{32}P radioactivity in the activated sulfur pellets, the calibration of the beta spectrometer was not very precise, and only a few useful results were obtained from our first set of measurements made on September 27, 1983 (Table 1).

A more precise calibration of the beta spectrometer was obtained in our second set of measurements by means of Cerenkov radiation counting. The ^{32}P radioactivity was measured by crushing several sulfur pellets and by dissolving and diluting a 5-g sample of each sulfur pellet to 50 ml. The counted samples were then spiked with a known quantity of ^{32}P using standard addition techniques and recounted to establish the Cerenkov radiation counting efficiency. The efficiency is zero below 260 keV and increases thereafter with beta particle energy so that low backgrounds are achieved in the counting of the high energy-beta particles from ^{32}P. The values which we obtained for relating

Table 1. Sulfur activation data from ORNL measurements at the Little Boy-Comet Critical Assembly.

Sulfur pellet number	Detector location	Initial ^{32}P radioactivity	
		dpm/g of S/10^{16} fission	RSD (%)[a]
Sept. 27, 1983[b]			
1-6	Surface-90°	594	11.2
1-7	90°	581	11.3
1-8	90°	572	11.2
1-15	200 cm-90°	14.8	19.4
March 13, 1984[c]			
2-1	75 cm-90°	93.7	4.8
2-2	75°	78.0	7.3
2-3	67.5°	67.3	3.5
2-4	60°	44.3	3.7
2-5	45°	14.8	4.8
2-6	30°	2.51	8.5
2-7	22.5°	2.34	10.3
2-8	15°	2.67	10.5
2-9	0°	2.85	9.7
2-10	Surface-90°	540	3.3
2-11	67.5°	112	3.4
2-12	45°	7.17	3.6
2-13	22.5°	4.17	4.5
2-14	0°	5.83	8.2
May 8, 1984[d]			
3-1	200 cm-90°	12.41	3.41
3-2	90°	13.14	3.48
3-3	90°	12.88	3.49
3-4	75 cm-90°	103.8	3.37
3-5	90°	102.5	3.38
3-6	90°	101.6	3.37
3-7	Surface-90°	591.7	3.39
3-8	90°	588.3	3.39
3-9	90°	592.7	3.39

[a] Relative standard deviation of measured sulfur-activation values.

[b] Two maximum-power operations (2.0 x 10^{16} fissions) inside Kiva 2.

[c] Three maximum-power operations (3.0 x 10^{16} fissions) inside Kiva 2.

[d] Three maximum-power operations (3.0 x 10^{16} fissions) outside Kiva 2.

disintegrations per minute per gram of sulfur (dpm/g of S) to counts per minute (cpm) of a sulfur pellet are given in Table 2. In our second and third sets of sulfur-activation measurements, the energy gain of the beta spectrometer was established very carefully using conversion electrons from a ^{137}Cs source, the spectral region between 160 keV and 2.0 MeV was integrated, and the background subtracted to obtain the net count rate for each sulfur pellet. These count-rate data and the weighted mean calibration factor for the beta spectrometer (Table 2) were used to estimate the disintegration rates of the ^{32}P radioactivity in the sulfur pellets exposed on March 13 and May 8, 1984 (Table 1).

The primary purpose of our second set of measurements was to obtain data on the angular distribution of the leakage of sulfur-activation neutrons from the Little Boy-Comet Critical Assembly (Table 1). Hence, we exposed a number of sulfur pellets at the surface and 75 cm from the center of the core and at various angles between the nose (0^{o}) and waist (90^{o}) as shown in Fig. 1. The results of our measurements at angular intervals of 15^{o} and 22.5^{o} are illustrated in Figs. 2 and 3, respectively. In the measurements made on an arc at 75 cm from the center of the core, we could easily determine the angle of the exposed sulfur pellets to within a couple of degrees. However, we encountered experimental difficulties in determining the angles of sulfur pellets exposed at the surface of the assembly. Note, for example, that the sulfur pellet exposed at the 75 cm-45^{o} detector location shows a greater activation than the sulfur pellet exposed at the surface-45^{o} detector location. This anomaly is probably due to a combination of the rapidly changing leakage of sulfur-activation neutrons at angles of

Table 2. Summary of calibration data for beta spectrometer.

Sulfur pellet number	Initial count rate (cpm)	Initial ^{32}P radioactivity (dpm/g of S)	Calibration factor (dpm/g of S/cpm)
2-1	166.2 ± 3.5%[a]	284.04 ± 5.2%[b]	1.7090 ± 6.3%
2-10	957.0 ± 0.5%	1625.6 ± 4.6%	1.6986 ± 4.7%
2-15	64.22 ± 2.2%	107.03 ± 5.8%	1.6666 ± 6.2%
		Weighted mean	1.6927 ± 3.2%

[a]Initial count rate of sulfur pellet and relative standard deviation as determined by beta spectrometer and by extrapolation back to time of exposure.

[b]Initial ^{32}P radioactivity and relative standard deviation as determined by Cerenkov radiation counting of a crushed and dissolved sample of sulfur from each pellet and by extrapolation back to time of exposure.

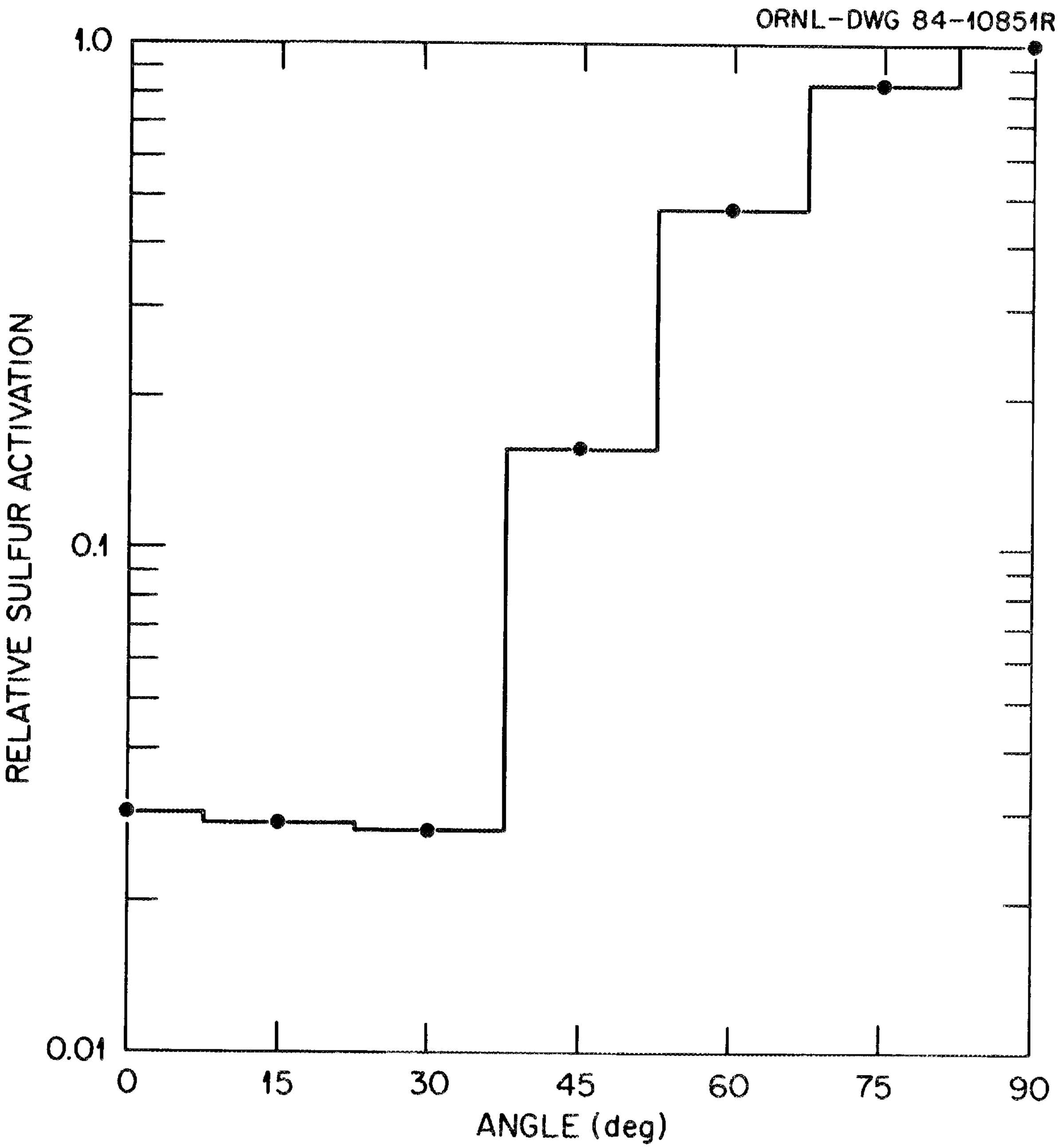

Figure 2. Experimental ORNL data on sulfur activation at 75 cm from the core and at angular intervals of 15° between the nose (0°) and waist (90°) of the reactor (Fig. 1). The data are normalized to sulfur activation at the 90° detector location.

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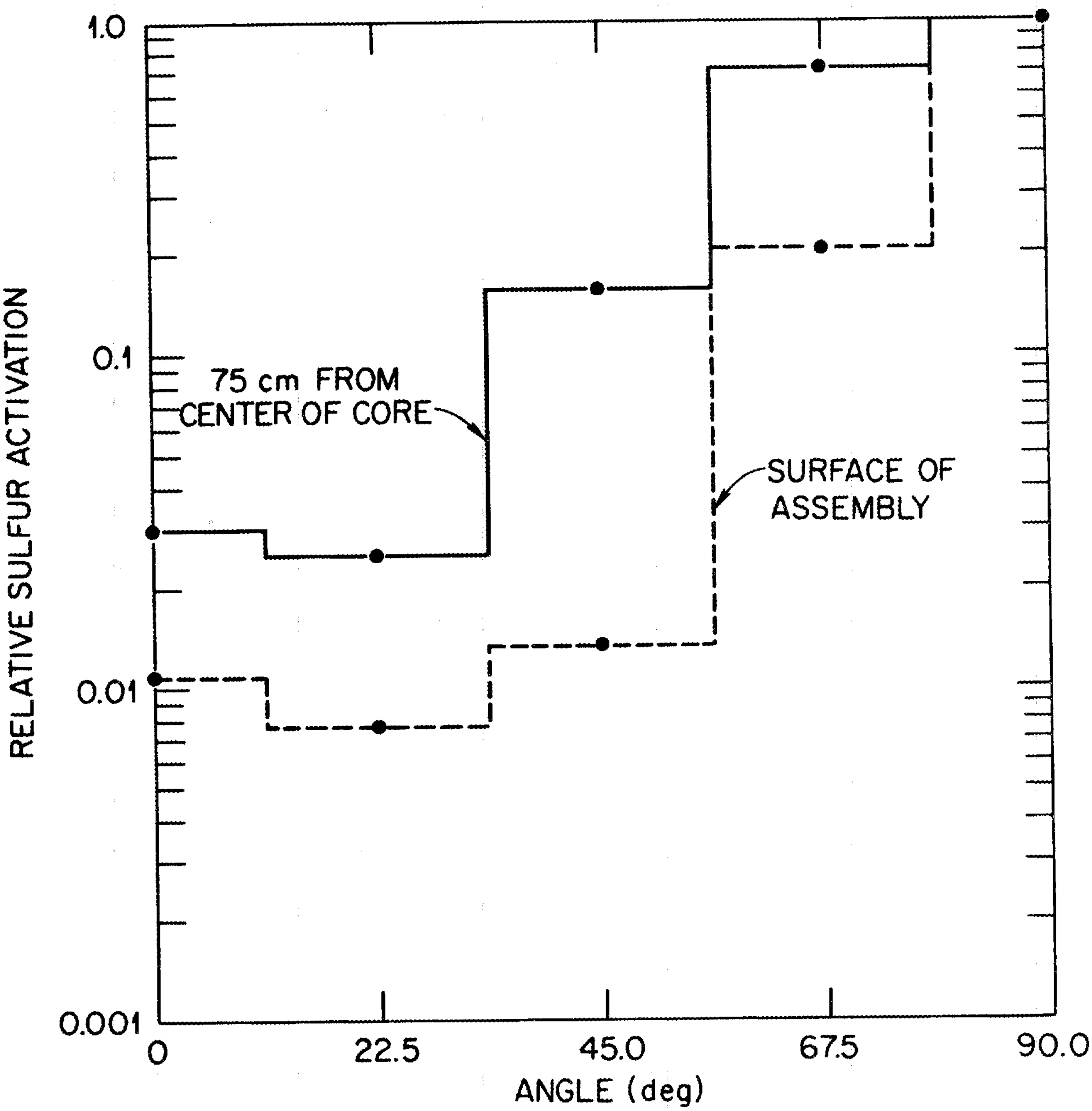

Figure 3. Experimental ORNL data on sulfur activation at the surface and 75 cm from the core and at angular intervals of 22.5° between the nose (0°) and waist (90°) of the reactor (Fig. 1). The data are normalized to sulfur activation at the 90° detector locations.

about 45^{0} and the experimental difficulties encountered in determining the angles for sulfur pellets exposed at the surface of the assembly. Only the angle for sulfur pellets exposed at the surface-90^{0} detector location could be determined to within a reasonable accuracy of a couple of degrees.

A troublesome aspect of our first and second set of measurements made inside Kiva 2 was the observed difference in the activation of sulfur at the surface-90^{0} detector location (Table 1). Hence, the purpose of our third set of measurements made outside Kiva 2 was to refine the sulfur-activation data taken at the waist (90^{0}) where we could accurately determine the angle of the exposed sulfur pellets. Note that the results of our third set of measurements at the surface-90^{0} location are more consistent with the results of our first set of measurements than those of our second set (Table 1). The results of our second set of measurements may be artificially low due to backscattering of low-energy neutrons into the reactor power-level instrumentation (i.e., the moderated and uncompensated BF_3 ion chamber) from close-by extraneous equipment as noted in reactor logbook entries for March 13, 1984.

The sulfur pellet exposures were normally made at the maximum reactor-power level of 170 watts permitted by various operational safety considerations.[18] However, we also exposed sulfur pellets at several other power levels during our second set of measurements (Table 3). A nonlinear response of the reactor power-level instrumentation at higher power levels was suggested by sulfur activation and other radiation measurements made by Straume and Dobson,[27] and they recommended that caution should be used when normalizing data obtained at different power

Table 3. Data on sulfur activation at varying reactor power levels.

Sulfur pellet number	Initial count rate (cpm)	Irradiation time (minutes)	Reactor power (watts)
2-10	957.0 ± 0.5%[a]	90[b]	170[c]
2-15	64.22 ± 2.2%	20	50
2-16	54.04 ± 2.4%	50	17
2-17	27.59 ± 3.6%	90	5

[a]Initial count rate of sulfur pellet and relative standard deviation as determined by beta spectrometer and by extrapolation back to time of exposure.

[b]Irradiation time of sulfur pellet exposed at surface-90^{o} detector location as shown in Fig. 1.

[c]Reactor power levels based on a value of 3.3×10^{10} fissions per second per watt and power calibration data provided by LANL.

levels. Our sulfur activation data for varying power levels failed to show any significant nonlinear response of the reactor instrumentation between 5 and 170 watts (Fig. 4). The backscattering of low-energy neutrons into the reactor power-level instrumentation from close-by extraneous equipment may cause normalization problems as noted previously.

Our relative angular-distribution data on sulfur activation by fast neutrons from the Little Boy-Comet Critical Assembly can be used with confidence (Figs. 2 and 3) because backscattered low-energy neutrons do not contribute to activation of sulfur by the $^{32}S(n,p)^{32}P$ threshold reaction. However, comparisons between measurements and calculations on an absolute basis should be limited to the sulfur-activation data from our third set of measurements made in the open area outside Kiva 2 (Table 1).

SULFUR-ACTIVATION CALCULATIONS

The leakage of fast neutrons from the Little Boy-Comet Critical Assembly has been calculated at LANL using Monte Carlo radiation transport techniques[5,11,33] and ORNL using discrete ordinates transport (DOT) techniques.[34-36] We have used the neutron-leakage spectra from these studies[33,34] and the cross sections for the $^{32}S(n,p)^{32}P$ reaction from the Vitamin-E (ENDF/B-5) Library[37] to calculate the expected initial ^{32}P radioactivity in the exposed sulfur pellets. The results of our calculations are given in Table 4. Neutron transport through the cylindrical steel shell surrounding the core causes a severe "softening" of the fission neutron spectrum. The average energy of the fast neutrons from fissions in ^{235}U is about 1 MeV, while the average

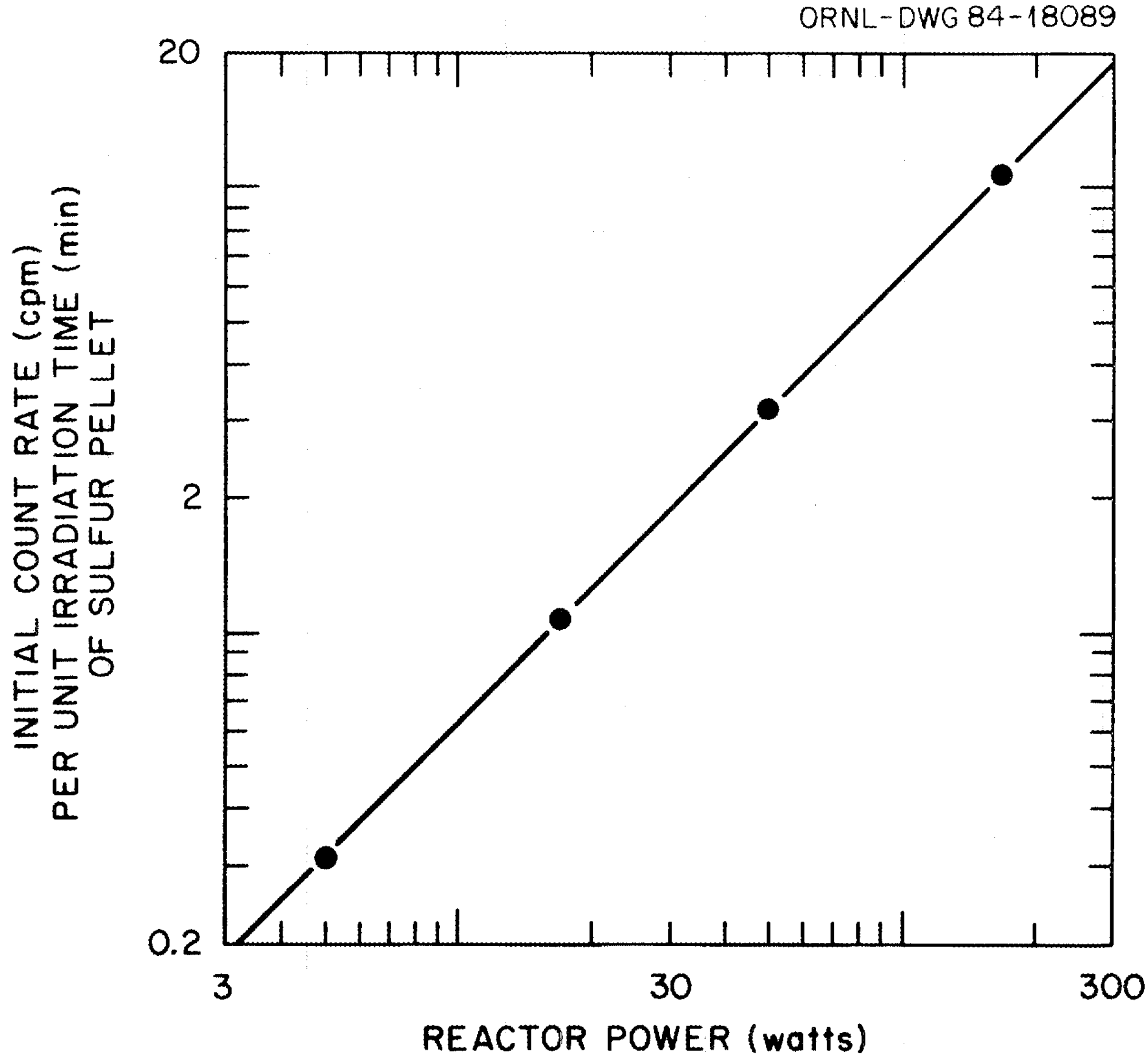

Figure 4. Experimental ORNL data on sulfur activation for varying reactor power levels. The sulfur pellets were exposed at the surface-90° detector location (Fig. 1).

Table 4. Sulfur-activation data obtained by using LANL and ORNL calculations of the neutron-leakage spectra from the Little Boy-Comet Critical Assembly.

Detector location[a]	Initial ^{32}P activity (dpm/g of S/fission)		Ratio
	LANL calculation	ORNL calculation	
75 cm-90°	7.37×10^{-15}	7.64×10^{-15}	0.97
67.5°	5.73×10^{-15}	5.03×10^{-15}	1.14
45°	1.10×10^{-15}	1.07×10^{-15}	1.03
22.5°	1.50×10^{-16}	1.51×10^{-16}	0.99
0°	2.15×10^{-16}	1.97×10^{-16}	1.09
200 cm-90°	1.05×10^{-15}	9.15×10^{-16}	1.15
67.5°	7.25×10^{-16}	6.62×10^{-16}	1.10
45°	2.54×10^{-16}	2.41×10^{-16}	1.05
22.5°	4.55×10^{-17}	4.27×10^{-17}	1.07
0°	2.13×10^{-17}	1.65×10^{-17}	1.29

[a]See Fig. 1.

energy of the fast neutrons leaking from the Little Boy-Comet Critical Assembly is only about 0.3 MeV. Very few of the leakage neutrons have energies greater than the effective threshold energy of about 2.5 MeV for the $^{32}S(n,p)^{32}P$ reaction, and the statistical uncertainties associated with LANL Monte Carlo calculations of the neutron-leakage fluences at energies greater than 2.5 MeV are quite large. These statistical uncertainties probably account for most of the observed differences in the ratios between the two sets of theoretical sulfur-activation data in Table 4.

A couple of comparisons can be made using the experimental and theoretical data on sulfur activation in Tables 1 and 4, respectively. Because of the low activation of sulfur near the nose (0 and 22.5^o) of the Little Boy-Comet Critical Assembly (Table 4), we could not measure the angular distribution of sulfur-activation neutrons at 200 cm from the core (Fig. 1). Hence, reliable experimental data on the angular distribution of sulfur-activation neutrons are only available at detector distances of 75 cm. These experimental ORNL data and the theoretical ORNL and LANL data are compared on a relative basis in Table 5 and Fig. 5. With the exception of the data at 22.5^o, the agreement is quite good ($\pm$ 15%). The overall agreement is not as good ($\pm$ 40%) when the various ORNL and LANL data at the waist (90^o) and the 75- and 200-cm detector locations are compared on an absolute basis (Table 6).

Our experimental and theoretical data on sulfur activation may contain several systematic errors. The potential systematic errors in the experimental data (Table 6) due to either the beta spectrometer calibration or power calibration data are probably small compared to potential systematic errors in the theoretical data.[17] For example,

Table 5. Comparison of theoretical and experimental data on the angular distribution of sulfur-activation neutrons from the Little Boy-Comet Critical Assembly.

Detector location[a]	Relative sulfur activation		
	ORNL measurement	LANL calculation	ORNL calculation
75 cm-90°	1.000[b]	1.000[c]	1.000[c]
67.5°	0.718	0.777	0.658
45°	0.158	0.149	0.140
22.5°	0.025	0.020	0.020
0°	0.030	0.029	0.026

[a]See Fig. 1.

[b]See Table 1 (Measurements on March 13, 1984).

[c]See Table 4.

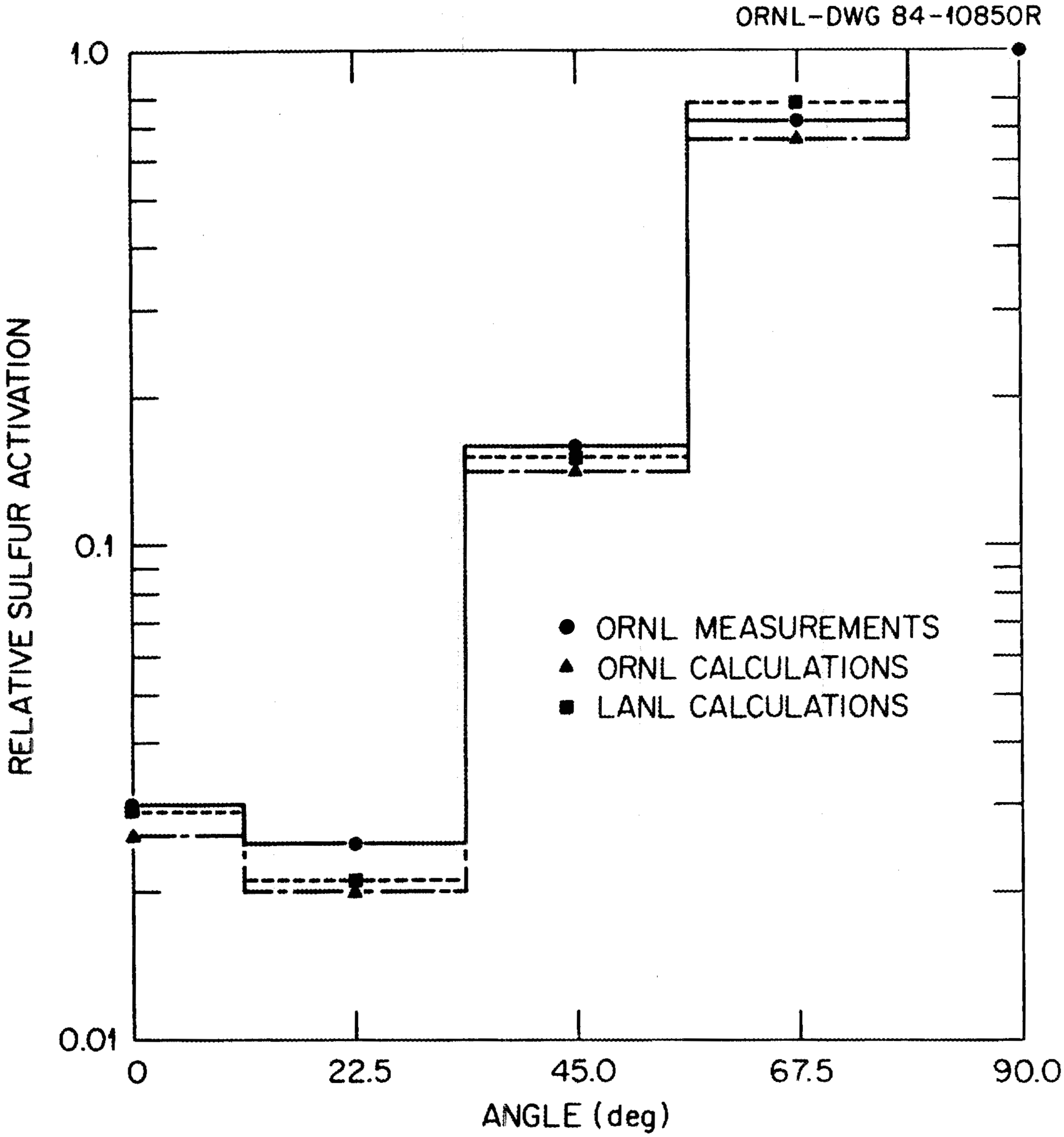

Figure 5. Comparison of measured and calculated data on sulfur activation at 75 cm from the core and at angular intervals of 22.5° between the nose (0°) and waist (90°) of the reactor (Fig. 1). The various data sets are normalized to sulfur activation at the waist detector locations.

Table 6. Comparison between experimental and theoretical data on sulfur activation at the Little Boy-Comet Critical Assembly.

Detector location[a]	Initial ^{32}P activity (dpm/g of S/fission)	Ratio of measurement to calculation
<u>200 cm-90°</u>		
ORNL measurement[b]	1.28×10^{-15}	
LANL calculation[c]	1.05×10^{-15}	1.22
ORNL calculation[c]	9.15×10^{-16}	1.40
<u>75 cm-90°</u>		
ORNL measurement[b]	1.03×10^{-14}	
LANL calculation[c]	7.37×10^{-15}	1.40
ORNL calculation[c]	7.64×10^{-15}	1.35

[a]See Fig. 1.

[b]See Table 1 (Measurements on May 8, 1984).

[c]See Table 4.

a systematic error as large as 15% may be embodied in both sets of theoretical sulfur-activation data (Table 6) due to uncertainties in the cross sections for the $^{32}S(n,p)^{32}P$ reaction. The theoretical neutron-leakage data also come from "deep penetration" calculations and may contain large uncertainties due to relatively small uncertainties in the cross-section data for the steel shell surrounding the core of the Little Boy-Comet Critical Assembly.[18] A detailed analysis of potential systematic errors in the theoretical neutron-leakage data will require the use of experimental data from a variety of radiation spectra and dose measurements.[11,17,18] The activation of sulfur is relevant to questions concerning the leakage of fast neutrons from the Little Boy-Comet Critical Assembly.[19,24,25]

SUMMARY

Studies of the activation of sulfur have been completed using the Little Boy-Comet Critical Assembly at the Los Alamos Critical Facility (Table 1 and Figs. 2 and 3). We have found good agreement between experimental and theoretical data on the angular distribution of sulfur-activation neutrons at 75 cm from the core and at various angles between the nose (0^o) and waist (90^o) of the reactor when the comparisons were made on a relative basis (Table 5 and Fig. 5). However, the agreement was not as good when comparisons were made at the waist (90^o) on an absolute basis (Table 6). Our sulfur-activation studies were performed as part of a larger program to provide benchmark data for the testing of methods used in recent source-term calculations for the Hiroshima bomb.

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