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TISSUE KERMA VS DISTANCE RELATIONSHIPS FOR INITIAL NUCLEAR RADIATION FROM THE ATOMIC DEVICES DETONATED OVER HIROSHIMA AND NAGASAKI

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ABSTRACT

Initial nuclear radiation is comprised of prompt neutrons and prompt primary gammas from an exploding nuclear device, prompt secondary gammas produced by neutron interactons in the environment, and delayed neutrons and delayed fission-product gammas from the fireball formed after the nuclear device explodes. These various components must all be considered in establishing tissue kerma vs distance relationships which describe the decrease of initial nuclear radiation with distance in Hiroshima and in Nagasaki.

An interest in initial nuclear radiation at distances of as much as two kilometers demands the economical use of discrete ordinates transport (DOT) techniques. The two-dimensional DOT-IV code developed at the Oak Ridge National Laboratory was used to calculate the tissue kerma in an air-over-ground geometry from prompt neutrons and prompt primary gammas and from prompt secondary gammas produced in air and ground. Data from the Los Alamos National Laboratory were used as the source terms.

The tissue kerma at ground level from delayed fission-product gammas and delayed neutrons was investigated using the NUIDEA code developed by Science Applications, Inc. This code incorporates very detailed models which can take into account such features as the rise of the fireball, the rapid radioactive decay of fission products in it, and the perturbation of the atmosphere by the explosion.

Tissue kerma vs distance relationships obtained by summing results of these current state-of-the-art calculations will be discussed. Our results clearly show that the prompt secondary gammas and delayed fission-product gammas are the dominant components of total tissue kerma from initial nuclear radiation in the cases of the atomic (or pure-fission) devices detonated over Hiroshima and Nagasaki.

INTRODUCTION

A program to revise the A-bomb dosimetry was formulated and implemented within the U.S. following the Symposium on Reevaluations of Dosimetric Factors: Hiroshima and Nagasaki, Department of Energy, Germantown, Maryland, September 5-6, 1982 (Ref. 1). The emphasis in the program to date has been on the revision of the tissue kerma vs distance relationships which describe the decrease in initial nuclear radiation with distance in Hiroshima and Nagasaki.

Initial nuclear radiation is the ionizing radiation released within the first minute after detonation, while the ionizing radiation released after the first minute is referred to as residual nuclear radiation[2-5] (see Tables 1 and 2). The initial nuclear radiation is comprised of the prompt neutrons and prompt primary gammas from an exploding device, the prompt secondary gammas emitted immediately after neutron interactions in the environment, and the delayed neutrons and delayed fission-product gammas from the fireball formed after the device explodes. Since the rapidly rising fireball reaches an altitude of about three kilometers or two miles by the end of the first minute, irradiation by the delayed neutrons and fission-product gammas ceases at ground level.[2] Sources of residual nuclear radiation are fission-product fallout and radioactivity produced by neutron activation of the ground beneath the explosion (see Tables 1 and 2).

Kerma is the sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing particles in a small volume element of a specified material divided by the mass of material in that volume element.[6-8] Units of kerma can be either grays (i.e., Gy) or rads (i.e., 0.01 Gy). The material volume of interest in a

Table 1. Components of ionizing radiation from a nuclear device[a]

Radiation component	Time emitted after detonation
Prompt fission and fusion neutrons[b]	<1 μsec
Delayed fission neutrons[c]	<1 min
Prompt fission gammas	<1 μsec
Gammas from inelastic scattering of neutrons	
From weapon	<1 μsec
From air	<10 μsec
From ground	<10 μsec
Gammas from neutron, charged-particle reactions	
From weapon	<1 μsec
From air	<10 μsec
From ground	<10 μsec
Neutron-capture gammas	
From weapon	<1 μsec
From air	Few msec to 0.2 sec
From ground	Few msec to 0.2 sec
Neutron-activation gammas[c]	
Early time	~0.2 sec to 1 min
Residual	1 min to years
Fission-product gammas[c]	
Early time	~0.2 sec to 1 min
Residual	1 min to years

[a]Abbott (Ref. 3) and Kukhtevich et al. (Ref. 4).

[b]No fusion neutrons are emitted by the atomic (or pure-fission) devices of interest here.

[c]It is estimated that more than two-thirds of the exposure to initial nuclear radiation occurs within the first second and that essentially all of the exposure to initial nuclear radiation occurs within the first ten seconds of the somewhat arbitrarily selected one-minute period of time which is used in making a distinction between initial and residual nuclear radiation (Ref. 2).

Table 2. Approximate source energies of ionizing radiation components from a nuclear device[a]

Radiation component	Energies (MeV)
Fusion neutrons[b]	~14
Prompt fission neutrons	0 - 20
Delayed fission neutrons[c]	0 - 0.7
Prompt fission gammas	0.02 - 10
Gammas from inelastic scattering of neutrons	
From nitrogen	0.7 - 7
From oxygen	2 - 7
From other elements of air and ground	0 - 8
Gammas from neutron, charged-particle reactions	
From nitrogen	0 - 7
From oxygen	~3.5
From other elements of air and ground	<2
Neutron-capture gammas	
From hydrogen	2.2[d]
From nitrogen	4 - 7.5, 10.8[d]
From other elements of air and ground	0 - >9
Neutron-activation gammas	0 - 2
Fission-product gammas[c]	0 - 6

[a]Abbott (Ref. 3) and Kukhtevich et al. (Ref. 4).

[b]No fusion neutrons are emitted by the atomic (or pure-fission) devices of interest here.

[c]The intensity and energy of the prompt neutrons and gammas depends more on the design and construction of a device than on the fissile materials used to fuel it. However, the fissile materials can have an important effect on the intensity and energies of the delayed neutrons and fission-product gammas emitted from the fireball formed after the device explodes (Ref. 5).

[d]Prominent secondary gammas produced by the capture of thermal neutrons (Ref. 3).

practical situation may be located in a medium of either similar or different composition. For example, the intensity of a radiation field can be specified in terms of tissue kerma in air. If the tissue volume (or tissue-equivalent detector) is so small that it does not appreciably disturb the radiation field, then the in-air tissue kerma from photons in rad units and the exposure in roentgen (or R) units will be nearly equal in magnitude (i.e., 1 R is approximately equal to 0.95 rad) (Ref. 9). However, exposure is applicable only in the case of photons, while in-air tissue kerma can be used in the case of both photons and neutrons. To convert our in-air tissue-kerma values into organ-dose values, one must take into account the shielding by overlying tissues of the body, the shielding by surrounding structures, and the production of secondary gammas in both the structural shielding materials and the body.

Some recently published factors for in-air tissue kerma from neutrons and gammas use the composition for either total body or total soft tissue of Reference Man as defined by the International Commission on Radiation Protection (ICRP) in 1975 (Ref. 10). The ICRP-1975 composition for total soft tissue of Reference Man is recommended over that for the total body.[11] Since the total body is a combination of the skeleton and total soft tissue, its use as a typical soft tissue is inappropriate, especially in the case of low energy photons. The ICRP-1975 composition for total soft tissue gives kerma factors[11] that are generally consistent with compositions for muscle tissue[9,12] and muscle equivalent plastic[12,13] which have been widely used as a typical soft tissue in both theoretical calculations and experimental measurements of in-air tissue kerma.

An interest in initial nuclear radiation at ground distances of as much as two kilometers (see Fig. 1) demands the economical use of discrete ordinates transport (DOT) techniques. The two-dimensional DOT-IV code developed at the Oak Ridge National Laboratory (ORNL) was used to calculate the tissue kerma in air over ground from prompt neutrons and prompt primary gammas and from prompt secondary gammas produced in air and ground.[14,15] Data of the Los Alamos National Laboratory (LANL) were used as the source terms.

The first modern calculations of the source terms for the Hiroshima and Nagasaki devices (i.e., the neutron and gamma leakage) were made in 1975 by Preeg at LANL (Ref. 18). His calculations were quickly done using available computer codes and one-dimensional (spherical) models of the devices. The one-dimensional model is a good approximation of the Nagasaki device which was a spherical plutonium-implosion design (see Fig. 2). However, the Hiroshima device was a radically different uranium gun-assembly device. Its design was two-dimensional (cylindrical), and the effects of its cylindrical construction are seen in measurements of the neutron activation of sulfur in Hiroshima.[19-21] The neutron and gamma leakage from a two-dimensional model of the Hiroshima device has been calculated by Whalen and his colleagues at LANL (Ref. 22-24), and their newer source-term data for both the Hiroshima and Nagasaki devices[24,25] were used in the DOT calculations of this study (see Tables 3 and 4).

The in-air tissue kerma at ground level from delayed neutrons and delayed fission-product gammas was investigated using the NUIDEA code developed by Science Applications, Incorporated (SAI) (Ref. 26).

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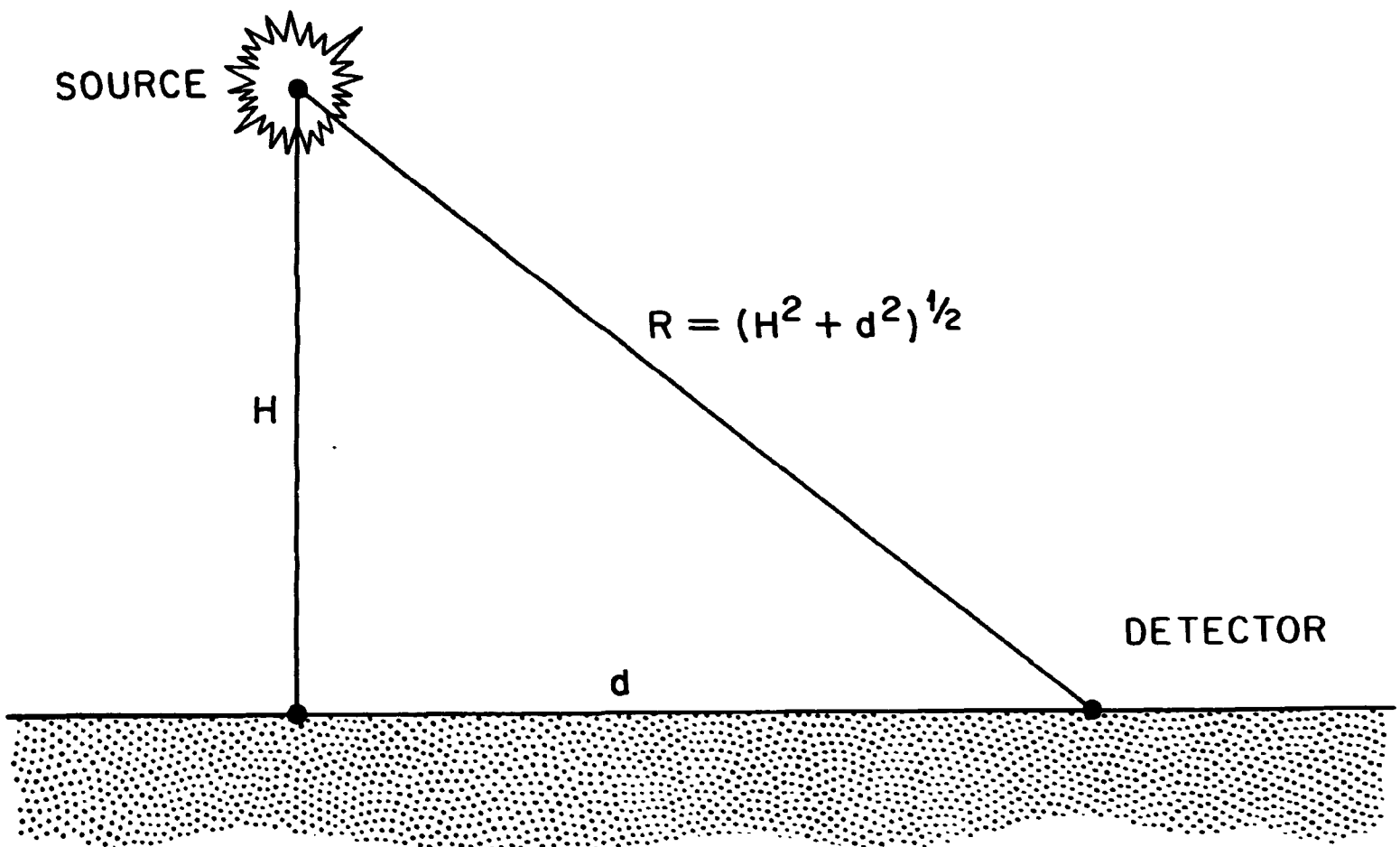

Fig. 1. Schematic illustrating the relationship between the burst height (H), ground distance (d), and slant distance (R).

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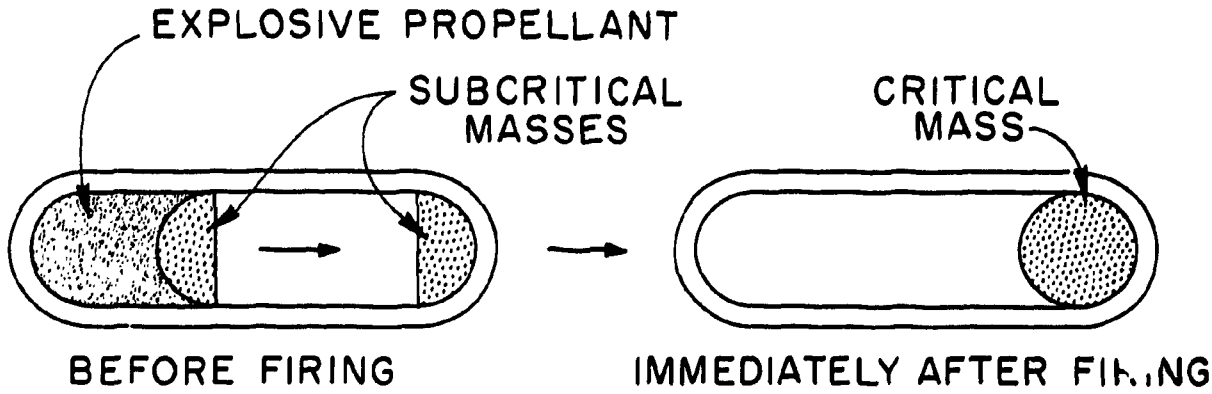
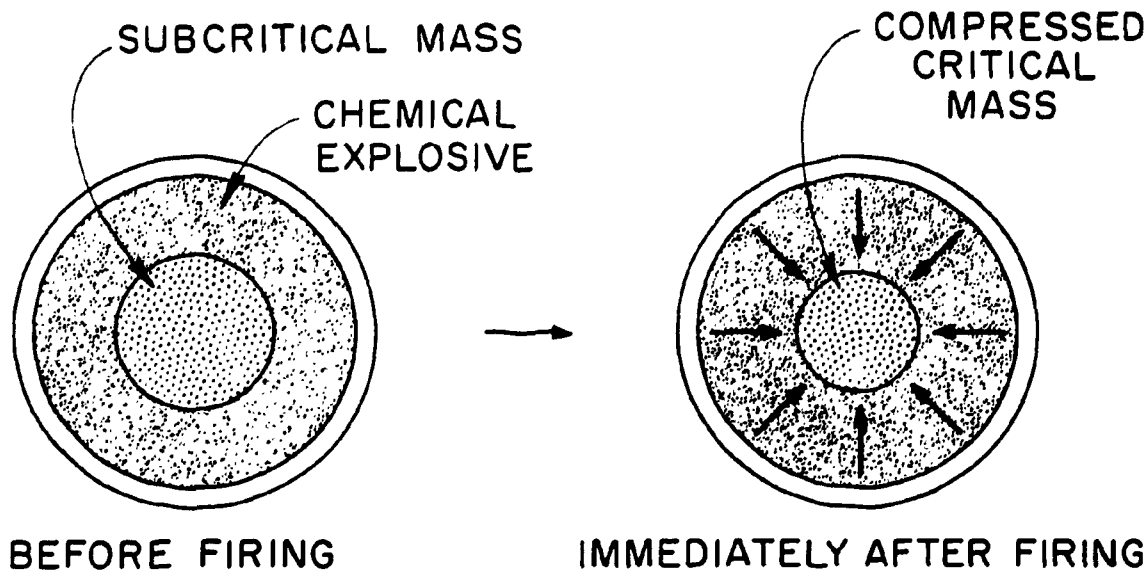


GUN ASSEMBLY DEVICE



IMPLOSION-TYPE DEVICE

Fig. 2. Schematic illustrating the principles of (a) a gun-assembly nuclear device and (b) an implosion-type nuclear device.

Table 7. Source energy spectra of prompt neutrons[a]

Energy interval (MeV)		Neutron leakage (neutrons kt^{-1})	
		Hiroshima	Nagasaki
1.390E-10 to	1.520E-7[b]		2.742E+18
1.520E-7	4.140E-7		1.248E+19
4.140E-7	1.130E-6		5.805E+19
1.130E-6	3.060E-6		2.658E+20
3.060E-6	8.320E-6		1.326E+21
8.320E-6	2.260E-5		5.226E+21
2.260E-5	6.140E-5	1.391E+19	1.682E+22
6.140E-5	1.670E-4	5.433E+19	4.186E+22
1.670E-4	4.540E-4	2.174E+20	7.101E+22
4.540E-4	1.235E-3	6.686E+20	2.631E+22
1.235E-3	3.350E-3	1.102E+21	3.869E+20
3.350E-3	9.120E-3	1.439E+21	4.947E+19
9.120E-3	2.480E-2	1.656E+22	4.162E+19
2.480E-2	6.760E-2	9.757E+21	5.482E+19
6.760E-2	1.840E-1	2.620E+22	1.007E+20
1.840E-1	3.030E-1	1.512E+22	6.354E+19
3.030E-1	5.000E-1	1.717E+22	7.420E+19
5.000E-1	6.400E-1	7.288E+21	8.113E+19
6.400E-1	8.230E-1	3.662E+21	7.475E+19
8.230E-1	1.060E+0	3.102E+21	6.993E+19
1.060E+0	1.353E+0	1.903E+21	9.004E+19
1.353E+0	1.738E+0	1.018E+21	1.111E+20
1.738E+0	2.232E+0	6.505E+20	1.324E+20
2.232E+0	2.865E+0	4.126E+20	1.820E+20
2.865E+0	3.680E+0	2.114E+20	8.523E+19
3.680E+0	4.730E+0	1.325E+20	7.595E+19
4.730E+0	6.070E+0	7.830E+19	5.855E+19
6.070E+0	6.880E+0	2.481E+19	2.166E+19
6.880E+0	7.790E+0	1.132E+19	1.355E+19
7.790E+0	8.830E+0	1.235E+19	7.155E+18
8.830E+0	1.000E+1	4.222E+18	4.257E+18
1.000E+1	1.100E+1	2.168E+18	1.309E+18
1.100E+1	1.200E+1	2.433E+18[c]	9.221E+17
1.200E+1	1.275E+1		4.619E+17
1.275E+1	1.350E+1		2.996E+17
1.350E+1	1.400E+1		2.197E+16
1.400E+1	1.450E+1		8.679E+16
1.450E+1	1.600E+1		5.816E+16

[a]Whalen (Ref. 24,25).

[b]Read as 1.390×10^{-10} to 1.520×10^{-7}, etc.

[c]Neutrons per kiloton from 1.100E+1 to 2.000E+1 MeV.

Table 4. Source energy spectra of prompt gammas[a]

Energy interval (MeV)	Gamma leakage (photons kt^{-1})	
	Hiroshima	Nagasaki
0.00E-0 to 5.00E-2	1.120E+18	1.640E+19
5.00E-2 1.00E-1	1.873E+19	5.718E+20
1.00E-1 2.00E-1	2.524E+20	2.327E+21
2.00E-1 3.00E-1	3.042E+20	2.216E+21
3.00E-1 4.00E-1	2.253E+20	2.243E+21
4.00E-1 5.00E-1	2.066E+20	2.339E+21
5.00E-1 6.00E-1	2.054E+20	2.202E+21
6.00E-1 8.00E-1	2.969E+20	3.327E+21
8.00E-1 1.00E-1	4.842E+20	2.674E+21
1.00E+0 1.50E+0	2.734E+20	5.632E+21
1.50E+0 2.00E+0	1.626E+20	5.189E+21
2.00E+0 2.50E+0	1.446E+20	3.908E+21
2.50E+0 3.00E+0	1.030E+20	1.954E+21
3.00E+0 4.00E+0	1.162E+20	3.001E+21
4.00E+0 5.00E+0	6.324E+19	2.172E+20
5.00E+0 6.00E+0	3.692E+19	4.465E+19
6.00E+0 7.00E+0	3.325E+19	1.802E+19
7.00E+0 8.00E+0	7.348E+19	3.510E+19
8.00E+0 9.00E+0	2.036E+19	4.779E+18
9.00E+0 1.00E+1	1.566E+19	5.986E+17

[a]Whalen (Ref. 24,25).

This code incorporates very detailed models which can take into account such features as the rise of the fireball, the rapid early-time decay of fission products in it, and the perturbation of the atmosphere by the explosion.[27,28] It was assumed in these calculations that all fissions in the Hiroshima device occured in ^{235}U and that the Nagasaki device had about 80% of its fission in the ^{239}Pu core and 20% in the ^{238}U tamper surrounding the core.

Some other parameters needed in our radiation transport calculations are the energy yield of the device, the height of the explosion, the density profile and water vapor content of the air, and the ground composition including water content. The environmental parameters are difficult to obtain or even to estimate in some cases. Previously, a four element soil typical of that at the Nevada Test Site in the U.S. was used in approximating the ground in the two cities,[17] and a U.S. Standard (40^{o} N. Latitude) Atmosphere was used in estimating atmospheric conditions at the explosion heights (or burst heights) of the two devices.[17,29] The Hiroshima device exploded at a height of 580 m (or 1900 ft) over the center of the city (see Fig. 3) about 0815 hours on 6 August 1945, and the Nagasaki device exploded at a height of 503 m (or 1650 ft) over the Urakami Valley in the northern part of the city (see Fig. 4) about 1102 hours on 9 August 1945 (Ref. 30-32). The energy yields of the Hiroshima and Nagasaki explosions are assumed to be equivalent to 12.5 and 22 kt of TNT, respectively.[33-35]

DENSITY PROFILE AND WATER VAPOR CONTENT OF AIR

Our current best estimates of the density profile and water vapor content of the atmosphere at the times of the bombings (ATB) are

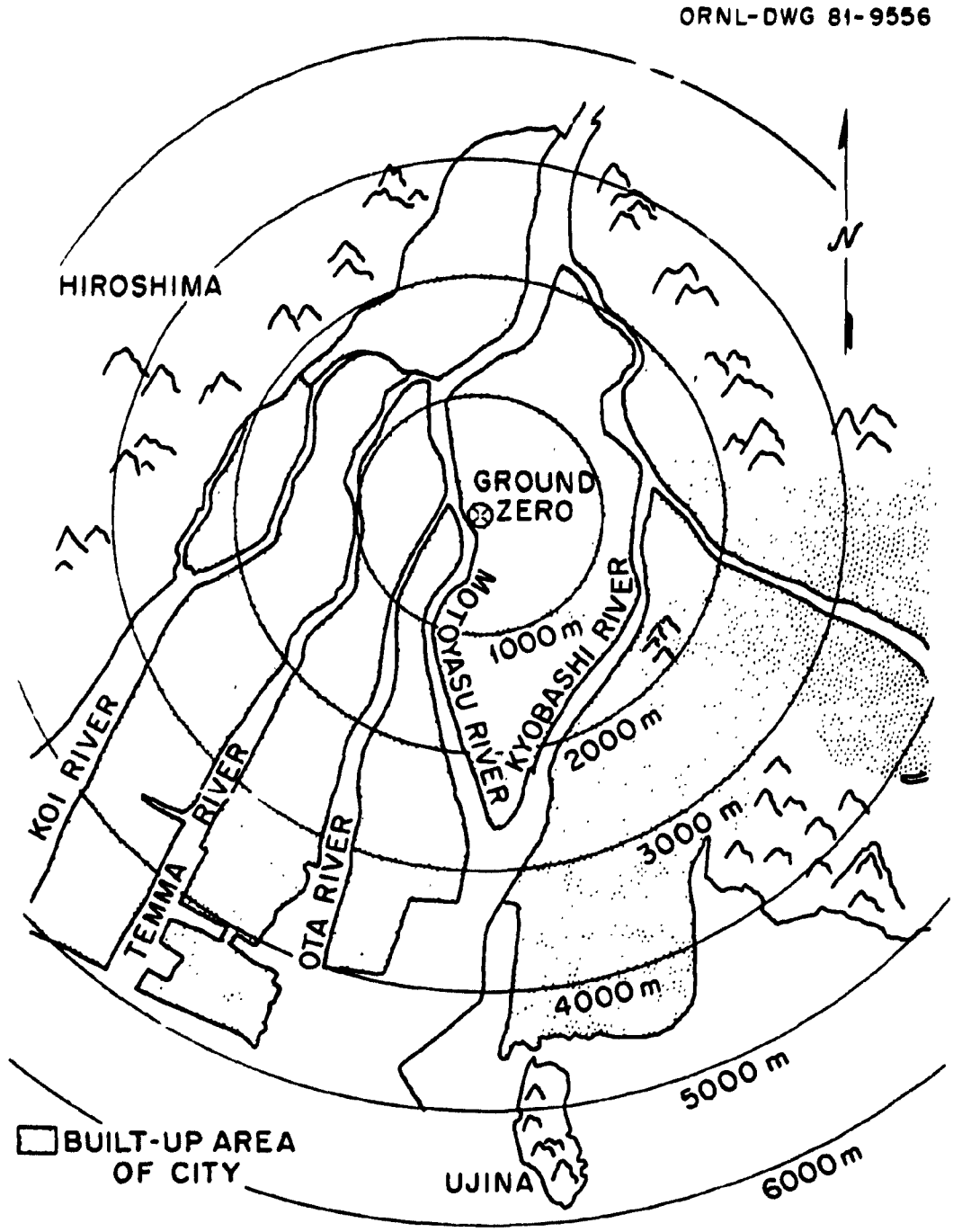


Fig. 3. Map showing built-up areas and location of hypocenter (or ground zero) in Hiroshima.

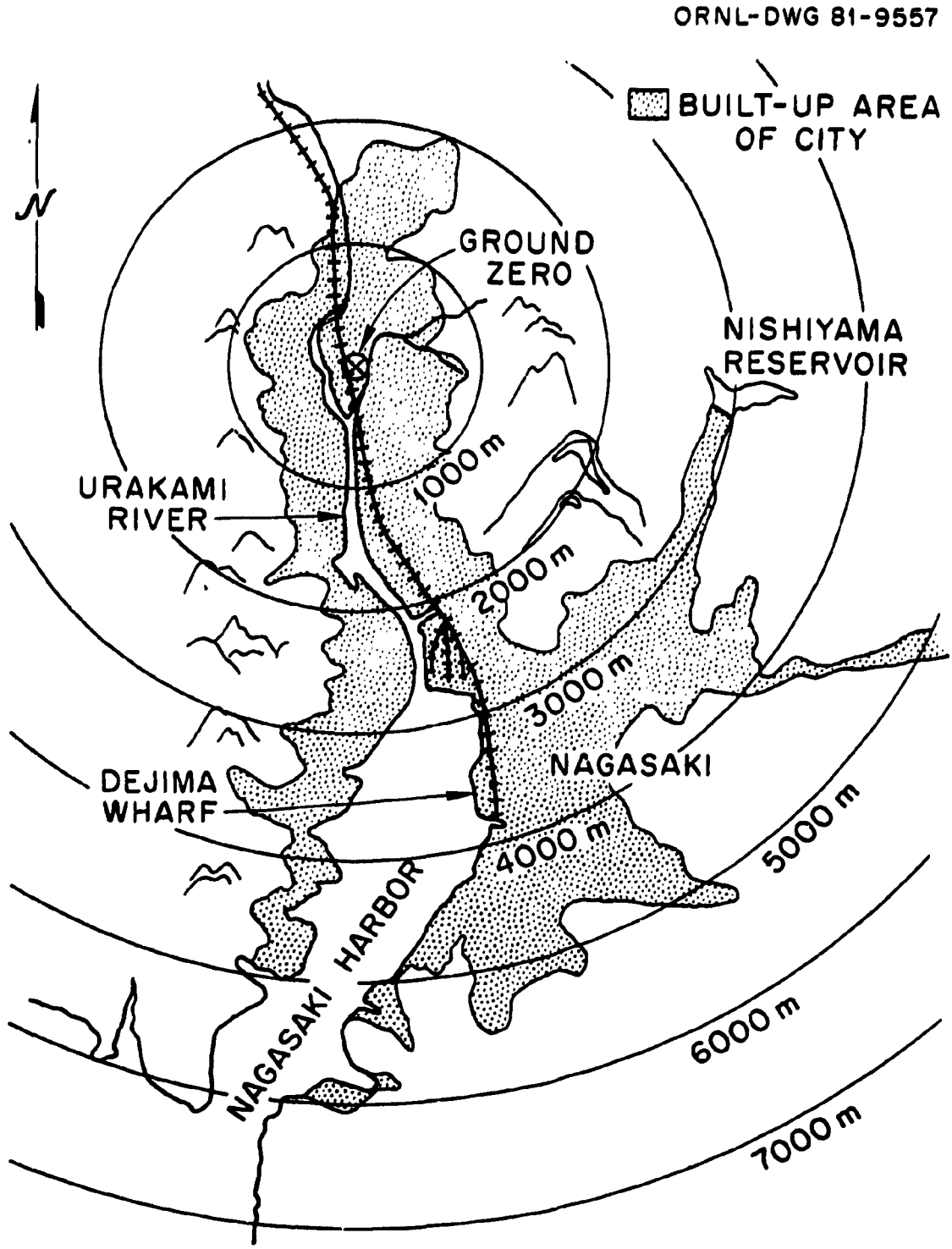


Fig. 4. Map showing built-up areas and location of hypocenter (or ground zero) in Nagasaki.

summarized in Table 5. These estimates are based on weather conditions aloft over Southern Japan ATB (see Appendix A) and on surface weather conditions in Hiroshima and Nagasaki ATB (Ref. 32,36-39) (see Tables 6 and 7). The visibilities at ground level come from a 1945 collection of surface weather data in the two cities by Castles[38] of the U.S. Strategic Bombing Survey (USSBS) in Japan.[40,41] The USSBS collection by Castles,[38] which was found during a recent search of storage files at ORNL, also provides valuable data from radiosonde measurements made over Fukuoka on 5 August 1945 at 2200 hours, Toyohasi on 6 August 1945 at 2200 hours, and Tokyo on 6 and 9 August 1945 at 0600, 1000, 1400, 1800, and 2200 hours (see Appendix A). These data on weather conditions over Southern Japan ATB indicate that the temperatures aloft were warmer and the humidities aloft were higher than those predicted by a U.S. Standard Atmosphere[31-33] (see Table 8).

The temperature, T, and pressure, P, at the altitude, Z, of interest were calculated by using the ground-level temperature, T_o, and pressure, P_o, and the equations:[42-44]

$$T = T_o - \alpha Z \text{ , and } P = P_o (T/T_o)^n \text{ ,} \qquad (1)$$

where α is the temperature lapse rate, and n is a constant which is dependent on α. The value of n is equal to $G_o/\alpha R_d$ where G_o is the gravitational constant and R_d is the gas constant for dry air (see Table 9). The mixing ratio, w, defined as the ratio of the mass of water vapor to the mass of dry air in a specified volume, was estimated at the altitude, Z, using the empirical model (see Appendix A):

$$w = w_o \exp(-\beta Z) \text{ ,} \qquad (2)$$

Table 5. Summary of data on density profile and water vapor content of atmosphere used in radiation transport calculations

Parameter	Hiroshima	Nagasaki
Air pressure (mb):		
Ground level[a]	1018	1014
Burst height	952	958
Air temperature (°C):		
Ground level[a]	26.7	28.8
Burst height	23.3	25.9
Relative humidity (%):		
Ground level[a]	80	71
Burst height	75	67
Moist air density (kg m^{-3}):		
Ground level	1.170	1.158
Burst height	1.110	1.106
Dry air density (kg m^{-3}):		
Ground level	1.150	1.137
Burst height	1.094	1.090
Absolute humidity (kg m^{-3}):		
Ground level	0.02025	0.02018
Burst height	0.01564	0.01613
Mean densities (kg m^{-3}):[b]		
Moist air	1.140	1.132
Dry air	1.122	1.114
Water vapor	0.01785	0.01808

[a]Surface weather conditions in Hiroshima at 0800 hours on 6 August 1945 (see Table 6) and Nagasaki at 1100 hours on 9 August 1945 (see Table 7).

[b]Between ground level and burst height of either 580 m in Hiroshima or 503 m in Nagasaki.

Table 6. Surface weather conditions in Hiroshima on 6 August 1945[a]

Time (hr)	Air pressure (mb)	Air temperature (°C)	Relative humidity (%)	Wind velocity ($m\ s^{-1}$)	Visibility
0100	16.0[b]	25.0	88	NNE 2.0	7[c]
0200	16.1	24.7	90	NNE 2.0	7
0300	16.1	24.2	92	NNE 1.5	7
0400	16.7	23.9	93	NNE 2.5	7
0500	16.9	23.7	93	NNE 2.3	7
0600	17.5	23.6	94	NNE 2.3	6
0700	18.0	24.7	89	NNE 1.3	6
0800	18.1	26.7	80	N 0.8	8
0900	18.0	27.3	79	SW 1.7	5
1000	18.5	29.3	67	SW 2.5	5
1100	17.7	30.0	65	W 2.8	4
1200	16.7	30.7	64	SSW 3.3	4
1300	16.1	30.7	64	SW 3.7	5
1400	15.9	31.0	66	SW 3.2	5
1500	15.3	30.3	70	SW 3.8	5
1600	15.2	30.7	65	SW 4.0	5
1700	15.1	29.7	72	SW 5.5	6
1800	15.5	28.3	78	SW 5.2	6
1900	16.1	28.2	77	SSW 3.0	6
2000	16.4	27.5	83	SSE 5.2	6
2100	17.3	26.9	79	S 3.7	6
2200	17.2	26.7	78	S 2.3	6
2300	17.3	26.6	78	SW 1.5	6
2400	16.9	26.5	75	WSW 2.5	6

[a]Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki (Ref. 32), Jablon (Ref. 36), Uda et al. (Ref. 37), and Castles (Ref. 38). Data taken from records of the Hiroshima Meterological Observatory located 3.6 km SSW of the hypocenter in Hiroshima.

[b]Add 1,000 millibars (or mb) to values in table.

[c]The above value from a 10-stage system for specifying the visibility means as follows (Ref. 2,38,39):

Stage	Maximum visible range (m)	Typical atmospheric conditions
4	1,000 - 2,000	Light fog or very dense haze
5	2,000 - 4,000	Dense haze
6	4,000 - 10,000	Light haze
7	10,000 - 20,000	Clear
8	20,000 - 50,000	Very clear

Table 7. Surface weather conditions in Nagasaki on 9 August 1945[a]

Time (hr)	Air pressue (mb)	Air temperature (°C)	Relative humidity (%)	Wind velocity ($m\ s^{-1}$)	Visibility
0100	15.0[b]	24.0	88	0	6[c]
0200	15.0	24.0	90	0	6
0300	14.8	23.5	91	ESE 0.7	6
0400	14.7	23.2	90	E 3.2	6
0500	14.6	23.2	87	0	6
0600	15.0	23.1	90	0	6
0700	15.0	24.3	94	ESE 2.2	6
0800	15.0	25.7	91	ESE 1.2	7
0900	15.3	27.3	86	ESE 1.8	8
1000	15.3	28.0	76	0.3	8
1100	14.0	28.8	71	SW 3.0	8
1200	13.9	29.4	68	SW 3.7	8
1300	13.6	29.9	58	SW 4.2	8
1400	13.3	29.9	65	SW 4.3	8
1500	13.0	29.9	63	SW 5.0	8
1600	12.7	29.3	66	WSW 6.0	8
1700	12.7	28.5	68	SW 3.3	8
1800	12.8	27.2	73	SW 6.2	8
1900	12.7	26.4	80	SW 7.2	8
2000	13.0	25.7	84	WSW 2.0	7
2100	13.2	25.2	88	WSW 5.0	7
2200	13.5	24.9	91	SW 1.5	6
2300	13.0	24.7	91	SSW 0.8	6
2400	13.1	24.6	91	SSW 0.8	6

[a]Committee for the Compilation of Materials on Damage Caused by the Atomic Bombings in Hiroshima and Nagasaki (Ref. 32), Jablon (Ref. 36), and Castles (Ref. 38). Data taken from records of the Nagasaki Marine Observatory, formerly the Nagasaki Meterological Station, located 4.5 km SSE of the hypocenter in Nagasaki.

[b]Add 1,000 millibars (or mb) to values in table.

[c]The above value from a 10-stage system for specifying the visibility means as follows (Ref. 2,38,39):

Stage	Maximum visible range (m)	Typical atmospheric conditions
6	4,000 - 10,000	Light haze
7	10,000 - 20,000	Clear
8	20,000 - 50,000	Very clear

Table 8. Comparison of atmospheric conditions at burst height estimated by using a U.S. Standard Atmosphere and Southern Japanese Atmosphere at the times of the bombings (ATB)

Parameter	U.S. Standard Atmosphere	Southern Japan Atmosphere ATB
Hiroshima (burst height = 580 m)		
Air pressure (mb)[a]	952	952
Air temperature (°C)[a]	22.9	23.3
Mixing ratio (g kg^{-1})[a]	1.356	1.429
Moist air density (kg m^{-3})[b]	1.112	1.110
Dry air density (kg m^{-3})[b]	1.097	1.094
Absolute humidity (kg m^{-3})[b]	0.01484	0.01564
Relative Humidity (%)[b]	72	75
Nagasaki (burst height = 503 m)		
Air pressure (mb)[a]	958	958
Air temperature (°C)[a]	25.5	25.9
Mixing ratio (g kg^{-1})[a]	1.415	1.480
Moist air density (kg m^{-3})[b]	1.108	1.106
Dry air density (kg m^{-3})[b]	1.092	1.090
Absolute humidity (kg m^{-3})[b]	0.01541	0.01613
Relative humidity (%)[b]	65	67

[a]Calculated by using Eqs. 1 and 2 from text and surface weather conditions in either Hiroshima at 0800 hours on 6 August 1945 (see Table 6) or Nagasaki at 1100 hours on 9 August 1945 (see Table 7). The mixing ratios at ground level in Hiroshima and Nagasaki at these times were calculated to be 1.761 and 1.774 grams of water vapor per kilogram of dry air.

[b]Calculated by using equations from Iribarne and Godson (Ref. 44) and Houghton (Ref. 45) and vapor pressures for saturated air from tables on pages D-93 to D-95 of the CRC Handbook of Chemistry and Physics (Ref. 46).

Table 9. Empirical constants for a U.S. Standard Atmosphere and Southern Japan Atmosphere at the times of the bombings (ATB)

Empirical constant	U.S. Standard Atmosphere	Southern Japan Atmosphere ATB
α (°K km^{-1})	6.5[a]	5.8[b]
n (unitless)	5.2561	5.8905
L (km)	2.2[c]	2.8[d]
β (km^{-1})	0.45	0.36

[a]National Advisory Committee for Aeronautics, Report 1235 (Ref. 42) and Iribarne and Godson (Ref. 44).

[b]Constant lapse rate obtained by applying method of least squares to pooled data on T vs Z between approximately 1 and 10 km in Tables A1 and A2 of Appendix A. A standard deviation of about 0.2 °K per km is estimated for the above value. The time-dependent sets of data on T vs Z between 1 and 10 km in Tables A1 and A2 give temperature lapse rates ranging from a low of 5.3 to a high of 6.2°K per km.

[c]Estimated by using data on U' vs Z between 0 and 4 km for U.S. Standard Atmosphere in Table 3.25 of the Handbook of Geophysics and Space Environments (Ref. 43).

[d]Vertical e-folding distance of the mixing ratio obtained by applying method of least squares to pooled data on w vs Z between approximately 0 and 4 km in Tables A1 and A2 of Appendix A. A standard deviation of about 0.3 km is estimated for the above value. The time-dependent sets of data on w vs Z between 0 and 4 km in Tables A1 and A2 give values for the e-folding distance of the mixing ratio ranging from a low of 2 km to a high of 5 km.

where w_o is the mixing ratio at ground level, and β is the reciprocal of the vertical e-folding distance of the mixing ratio, L (see Table 9). The values of T, P, and w at the altitude, Z, were used to calculate other parameters of interest such as the densities of moist and dry air and the absolute and relative humidities.[44-46]

WATER CONTENT AND COMPOSITION OF GROUND

Several soil samples from Hiroshima and Nagasaki have been obtained and analyzed[47,48] (see Table 10). A larger study involving fifty samples of soils from the two cities was reported in 1969 by Hashizume et al. of the Japanese National Institute of Radiological Sciences (JNIRS) (Ref. 49,50). Their study focused on trace elements such as Na and Mn which were important neutron-activation sources of residual nuclear radiation and on water content which affected the ground albedo of the incident neutrons. The free water content of the fifty samples of soil collected by JNIRS in the summer of 1966 ranged from 25-35% by mass. A mean value of 30% was adopted in the JNIRS study of residual nuclear radiation from neutron activation near the hypocenters in Hiroshima and Nagasaki.[50]

The Oak Ridge study was undertaken to obtain additional data on the bulk constituents of soil and on the major trace elements which contributed to the secondary gamma component of the initial nuclear radiation. Two samples from undisturbed areas in each city were analyzed: one taken as close as possible to the hypocenter, and one taken at a larger ground distance from the hypocenter. In Hiroshima, for example, the samples were taken in the vicinity of the A-Bomb Dome and Hiroshima Castle. The results are tabulated in Appendix B. Our

Table 10. Comparison of ground compositions used in radiation transport calculations

Element	Percent by mass		
	Hiroshima	Nagasaki	Nevada Test Site
O	61.5[a]	62.4[a]	54.9[b]
Si	23.3	17.4	31.5
Al	5.0	7.1	12.7
H	3.7	4.0	0.9
K	2.5	0.8	
Fe	1.2	4.1	
Na	1.1	0.6	
C	0.8	1.7	
Ca	0.6	0.8	
Mg	0.2	0.6	
Others[c]	0.1	0.5	

[a]Based on the JNIRS value of 30% by mass for the free water content (Ref. 50) and 70% by mass of the ORNL values for dry soil near the hypocenter areas (see Appendix B). The density of moist soil in both cities was assumed to be 1.8 grams per cubic centimeter.

[b]See Table 4 of Pace, Knight, and Bartine (Ref. 17).

[c]See Appendix B to this report.

values for Na and Mn agree in general with the values previously reported by JNIRS (Ref. 50). The mean JNIRS value of 30% by mass for the free water content and 70% by mass of the ORNL values for dry soil composition near the hypocenters (see Appendix A) are used to approximate the ground composition in Hiroshima and Nagasaki ATB (see Table 10). The two distal samples were analyzed to obtain data for potential use in sensitivity studies which will be needed to establish the precision of the radiation transport calculations.

NEUTRON LEAKAGE

Several sets of data on the magnitude of the neutron leakage from the Hiroshima and Nagasaki devices[18,24,25,51,52] are summarized in Table 11. The experimental ORNL data of most interest come from a 1968 set of measurements by Auxier et al.[51] These ORNL measurements were done at the Burlington Arsenal using exact duplicates of the Hiroshima and Nagasaki devices (see Figs. 5 and 6). The Burlington Arsenal replaced the high explosive (HE) in the Nagasaki device and the cores in both devices with polyethylene and depleted uranium, respectively, and provided small bores for centering a ^{252}Cf fission-neutron source in the replacement cores. Neutron flux measurements made at a radius of two meters from the ^{252}Cf source (see Figs. 7 and 8) gave leakage values of 0.30 and 0.009 neutron per fission neutron born (or neutron from the ^{252}Cf source) for the Hiroshima and Nagasaki devices, respectively.[19]

The theoretical LANL data come from the 1975 set of calculations by Preeg[18] and the more recent set of calculations by Whalen.[24,25] These two sets of calculations both consider the dynamic effect of

Table 11. Comparison of data on number of source leakage neutrons

Source	Type of investigation	Investigators	Neutron leakage per fission neutron born[a]
Hiroshima device	LANL Monte Carlo calculation	Preeg, 1975 (Ref. 18)	0.34
	LANL Monte Carlo calculation	Whalen, 1982 (Ref. 24)	0.29
	ORNL experimental measurement	Auxier et al., 1968 (Ref. 51)	0.30
	ORNL experimental measurement	Thorngate et al., 1965 (Ref. 52)	0.31[b]
Nagasaki device	LANL Monte Carlo calculation	Preeg, 1975 (Ref. 18)	0.41
	LANL Monte Carlo calculation	Whalen, 1982 (Ref. 25)	0.39
	ORNL experimental measurement	Auxier et al., 1968 (Ref. 51)	0.0009

[a]Assumes that the average number of neutrons produced for each fission was 2.5 in the uranium-fueled Hiroshima device and 2.9 in the plutonium-fueled Nagasaki device.

[b]Neutron leakage measured by using a nuclear reactor (i.e., the Ichiban Critical Assembly) which had a spherical core of enriched uranium surrounded by spherical reflector and steel shells simulating the tamper and casing of the Hiroshima device.

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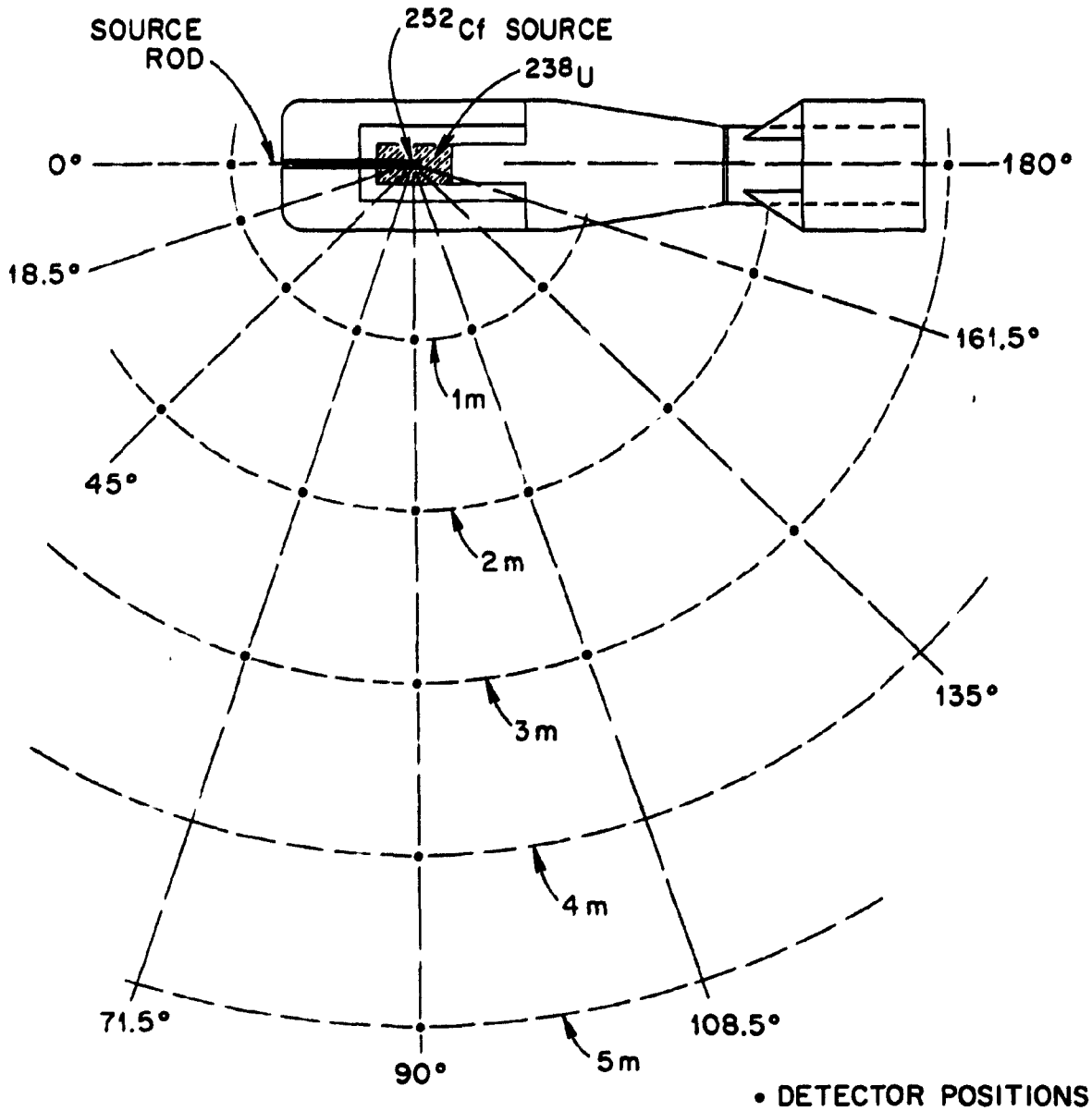

Fig. 5. Detector positions used in Oak Ridge National Laboratory measurements of neutron leakage from a duplicate of the Hiroshima device, looking down from above (Ref. 51).

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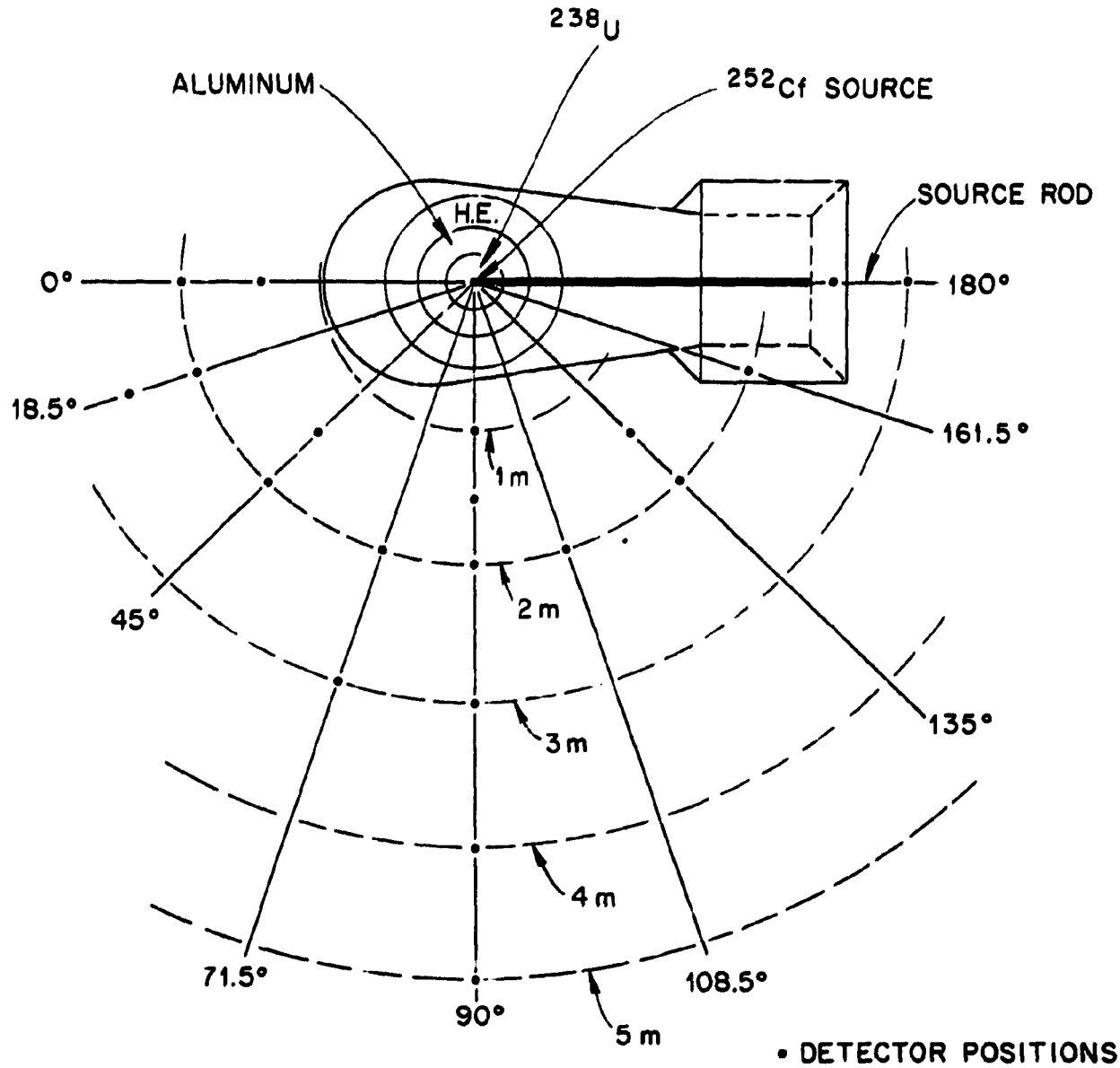

Fig. 6. Detector postions used in Oak Ridge National Laboratory measurements of neutron leakage from a duplicate of the Nagasaki device, looking down from above (Ref. 51).

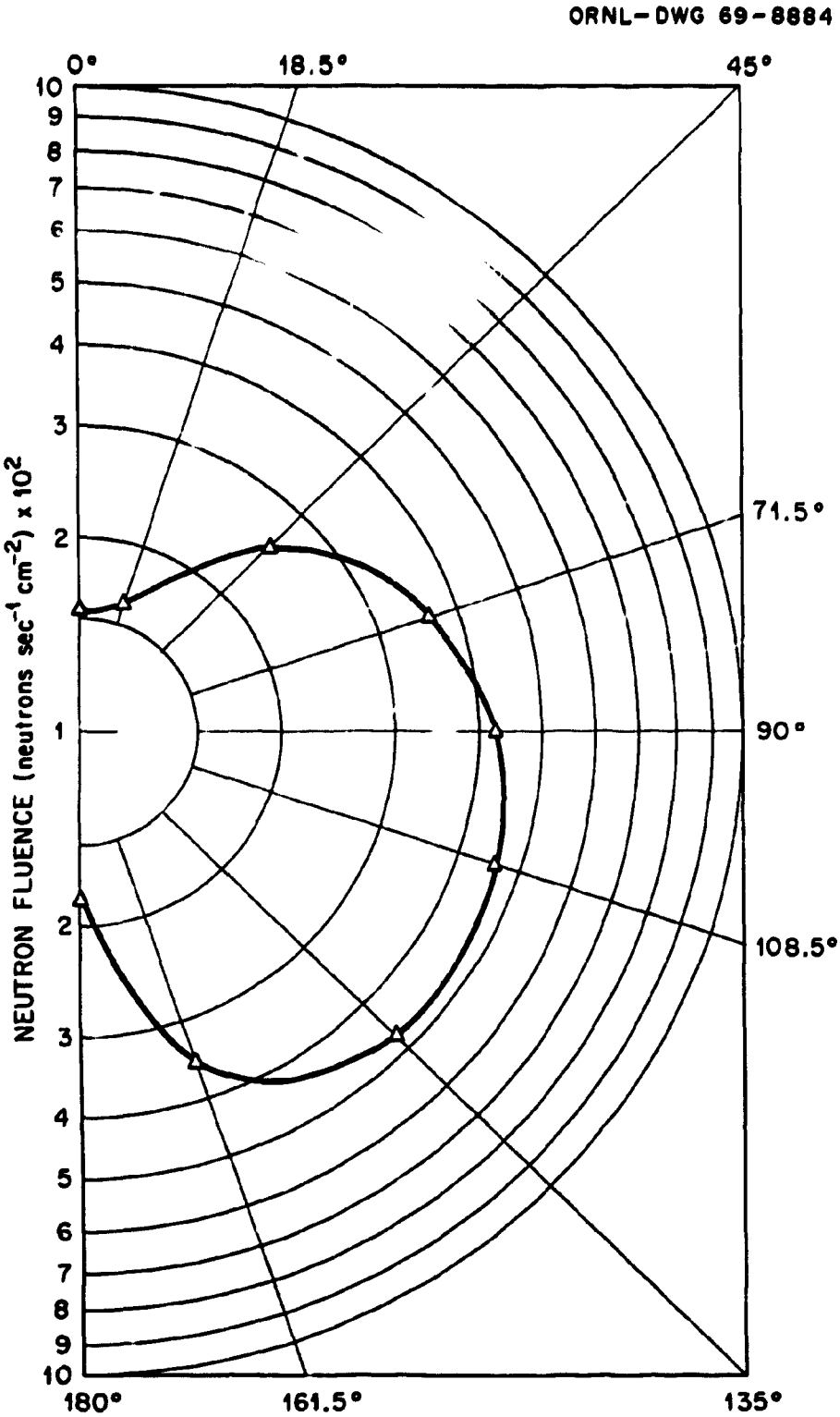

Fig. 7. Neutron flux measured at a radius of 2 m from a ^{252}Cf source at center of the core in the Hiroshima device (Ref. 51). The neutron emission rate of the source was 6.07E+5 neutrons per second.

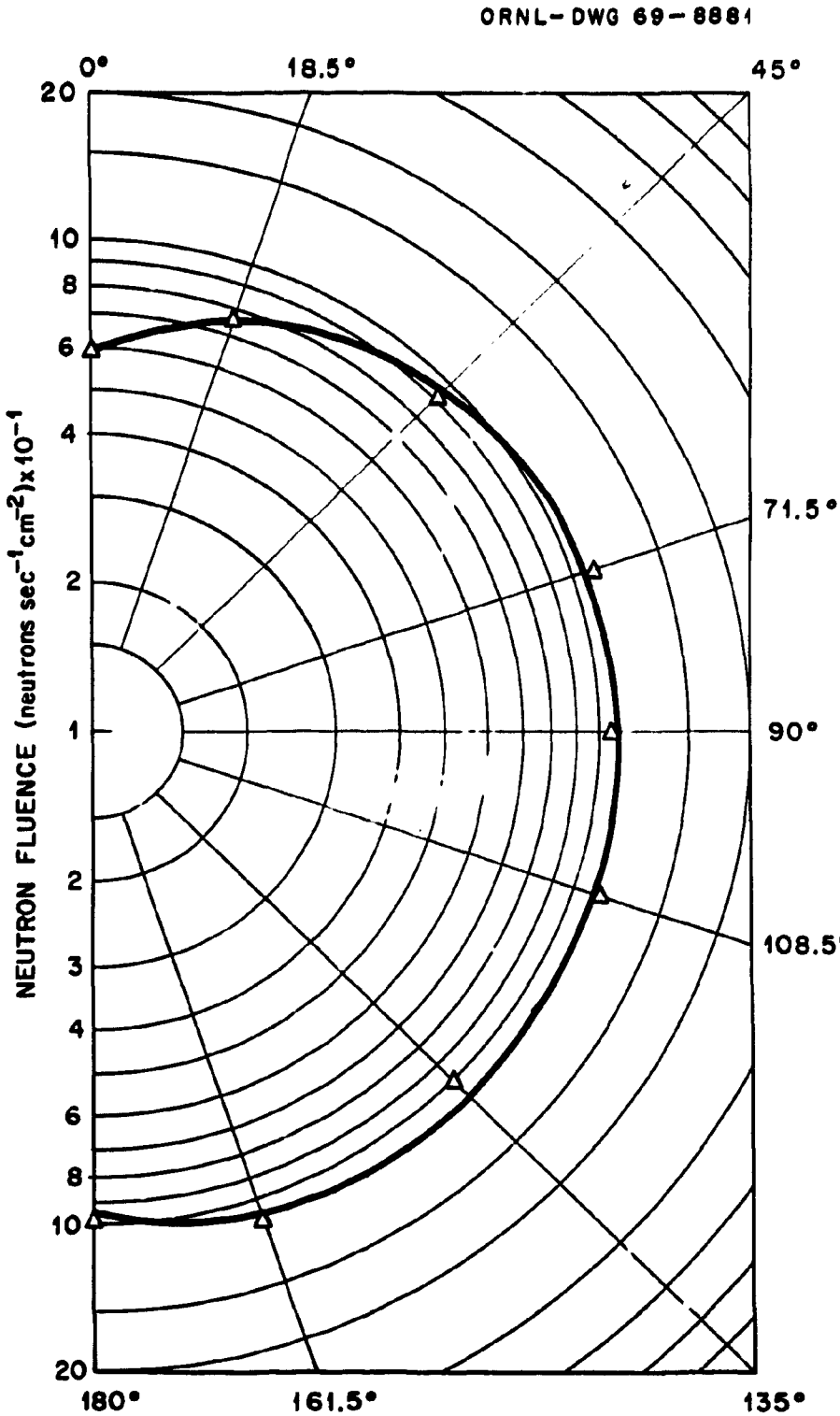

Fig. 8. Neutron flux measured at a radius of 2 m from a ^{252}Cf source at center of the core in the Nagasaki device (Ref. 51). The neutron emission rate of the source was 6.07E+5 neutrons per second.

weapon burnup on the neutron leakage. The theoretical LANL data and the experimental ORNL data for the Nagasaki device differ substantially (see Table 11). Most of the prompt fission-energy neutrons were quickly moderated down to thermal energies in the thick HE layer due to its high hydrogen content, and were then captured at a rate proportional to the reciprocal of their velocity, V (or square root of their kinetic energy, E), due to the cross section of the $^{1}H(n,\gamma)^{2}D$ reaction. Hence, escape was simply less favorable in the case of the lower-energy thermal neutrons from the "cold" device used in the ORNL measurements (e.g., the most probable energy of the thermal neutrons was about 0.025 eV) than in the case of the higher-energy thermal neutrons from the "hot" device considered in the LANL calculations (e.g., the probable energy of the bomb thermal neutrons was of the order of 200 eV) (see Table 3).

Only a very small fraction of the prompt fisson-energy neutrons escaped from the Nagasaki device as fast neutrons (i.e., less than 1% had energies greater than 10 keV), but they were quite energetic because of "hardening" of the fast-neutron spectrum by the hydrogen[53,54] in the thick HE layer. The leakage spectrum of fast neutrons from the Nagasaki device had an average energy of about 2 MeV, while the leakage spectrum of fast neutrons from the Hiroshima device had an average energy of only about 0.3 MeV. Most of the prompt fission-energy neutrons which escaped from the Hiroshima device were fast neutrons (i.e., more than 95% had energies greater than 10 keV), but they were severely degraded in energy because of "softening" of the fast-neutron spectrum by the iron[54,55] in its massive steel casing. Since mostly fast neutrons escaped from the Hiroshima

device, the dynamic effect of weapon burnup on the neutron leakage was less significant, and the theoretical LANL data and experimental ORNL data were found to be in close agreement (see Table 11).

ANISOTROPY OF THE NEUTRON LEAKAGE FROM THE HIROSHIMA DEVICE

Since the delayed neutrons have energies of less than 0.7 MeV (see Table 2), the ^{32}P radioactivity from neutron activation of sulfur is due entirely to prompt neutrons having energies greater than the effective threshold energy of 2.5 MeV for the $^{32}S(n,p)^{32}P$ reaction. The one-dimensional leakage (i.e., the energy spectrum) of prompt neutrons from the 1975 work by Preeg[18] was originally used to investigate the neutron activation of sulfur.[19-21] Experimental data for the Nagasaki device were available from sulfur-activation measurements made during the Crossroads Able test in 1946 and the Trinity test in 1945 (Ref. 56-58), and experimental data for the Hiroshima device were available from 1945 Japanese studies of the neutron activation of sulfur used as an adhesive material in binding the porcelain insulators to holders on electric poles.[59-62] These various experimental data and the theoretical sulfur-activation calculations were found to be in good agreement except at the smaller ground distance in Hiroshima. The large differences near the Hiroshima hypocenter were attributed by Kerr[19-21] to the inadequacy of the spherical gun-assembly model used in Preeg's 1975 work.[18]

The experimental ORNL measurements of the neutron leakage from a duplicate of the Hiroshima device, for example, show a blind spot in the neutron leakage through the nose section which was pointed downward ATB (see the 0^{o} and 18.5^{o} angles in Fig. 7). Original design

drawings were located[63,64] and used in a more realistic cylindrical gun-assembly model.[22-24] The two-dimensional leakage (i.e., the energy spectrum and angular distribution) of prompt neutrons has been calculated by Whalen[24] (see Fig. 9), and his theoretical LANL data on neutron leakage have been found to be in close agreement with the experimental ORNL data of Auxier et al.[51] Both sets of data show that the neutron leakage through the sides (i.e., 90^{o}) was about two and one-half times greater than that through the nose (i.e., 0^{o}). In the case of sulfur-activation neutrons having energies greater than approximately 2.5 MeV, however, the leakage through the sides was nearly five times greater than that through the nose (see Fig. 9). Hence, the neutron and gamma leakage from the Hiroshima gun-assembly device was a complex function of both energy and angle.

TRANSPORT OF PROMPT INITIAL NUCLEAR RADIATION

Transport of prompt initial nuclear radiation can be calculated very efficiently using DOT methods if the time-integrated, rather than time-dependent, particle flux (or particle fluence) will suffice, and the geometry is either one-dimensional (e.g., infinite air) or two-dimensional (e.g., air over ground). The two-dimensional calculations for an air-over-ground geometry require the use of a set of cross sections for neutrons and gammas having a broad energy-group structure. One such set, developed by ORNL at the request of the Defense Nuclear Agency (DNA), consists of 37 neutron and 21 gamma groups.[65] An initial investigation in 1976 (Ref. 16,17,19-21) with the DNA cross sections gave neutron results in Hiroshima that were 50% higher than

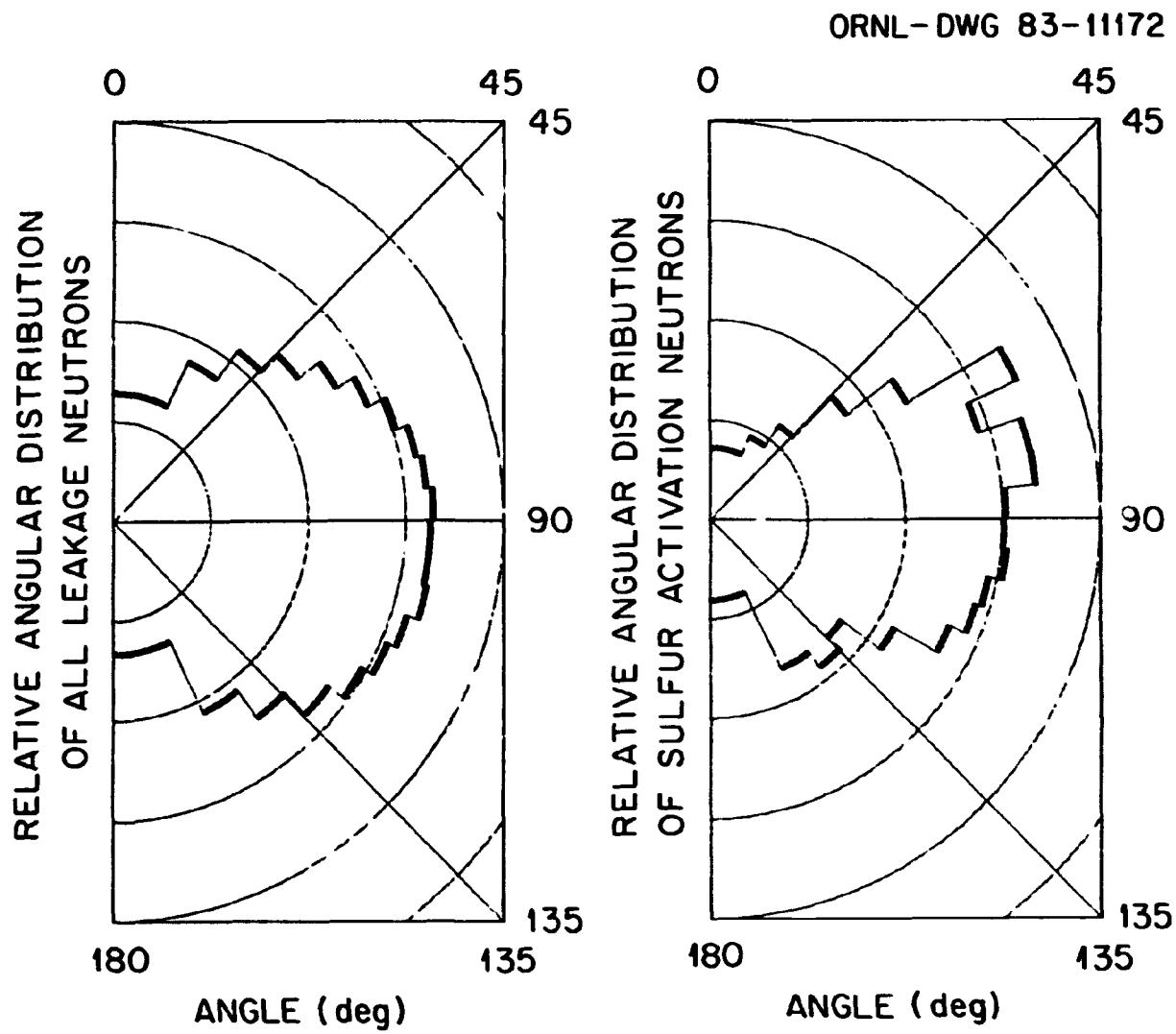

Fig. 9. Relative angular distribution of all leakage neutrons and sulfur-activation neutrons from the Hiroshima device as calculated by the Los Alamos National Laboratory (Ref. 24).

those later obtained by Loewe and Mendelsohn of the Lawrence Livermore National Laboratory (LLNL) (Ref. 66-68). It was eventually determined that the 1/E-weighted DNA cross sections did not properly represent scattering phenomena associated with the severely degraded-energy spectrum of prompt neutrons from the Hiroshima device. Hence, improved cross-section sets for the air environments in Hiroshima and Nagasaki ATB were created in 1981 using the Vitamin-C 171 neutron/36 gamma fine group set of cross sections[16,17] and more recently using the Vitamin-E 174 neutron/38 gamma fine group set. These fine group sets of cross sections were collapsed into the DNA broad energy-group structure with the one-dimensional ANISN code.[69]

The two-dimensional calculations with the DOT-IV code[16,17] used a cylindrical air-over-ground geometry with an idealized flat-ground surface as illustrated in Fig. 10. Six radial zones extending out to ground distances of 2820 m and seven horizontal zones of moist air with a deceasing density up to altitudes of 1419 m in Hiroshima and Nagasaki were defined. The mean moist-air density in each of the seven horizontal zones (see Fig. 10) was calculated by using Eqs. 1 and 2 together with the appropriate surface weather conditions in the two cities ATB (see Tables 6 and 7) and the empirical constants for the atmosphere over Southern Japan ATB (see Table 9). Cross-section sets with the standard DNA energy-group structure were created for each of the 42 air zones in the two cities through ρR-scaling of the ANISN infinite-air results where R is the slant distance to the mid-point of an air zone and ρ is the height-dependent density of moist air along R. Use of the ρR-weighted cross sections provides a better representation of the scattering phenomena in regions where the

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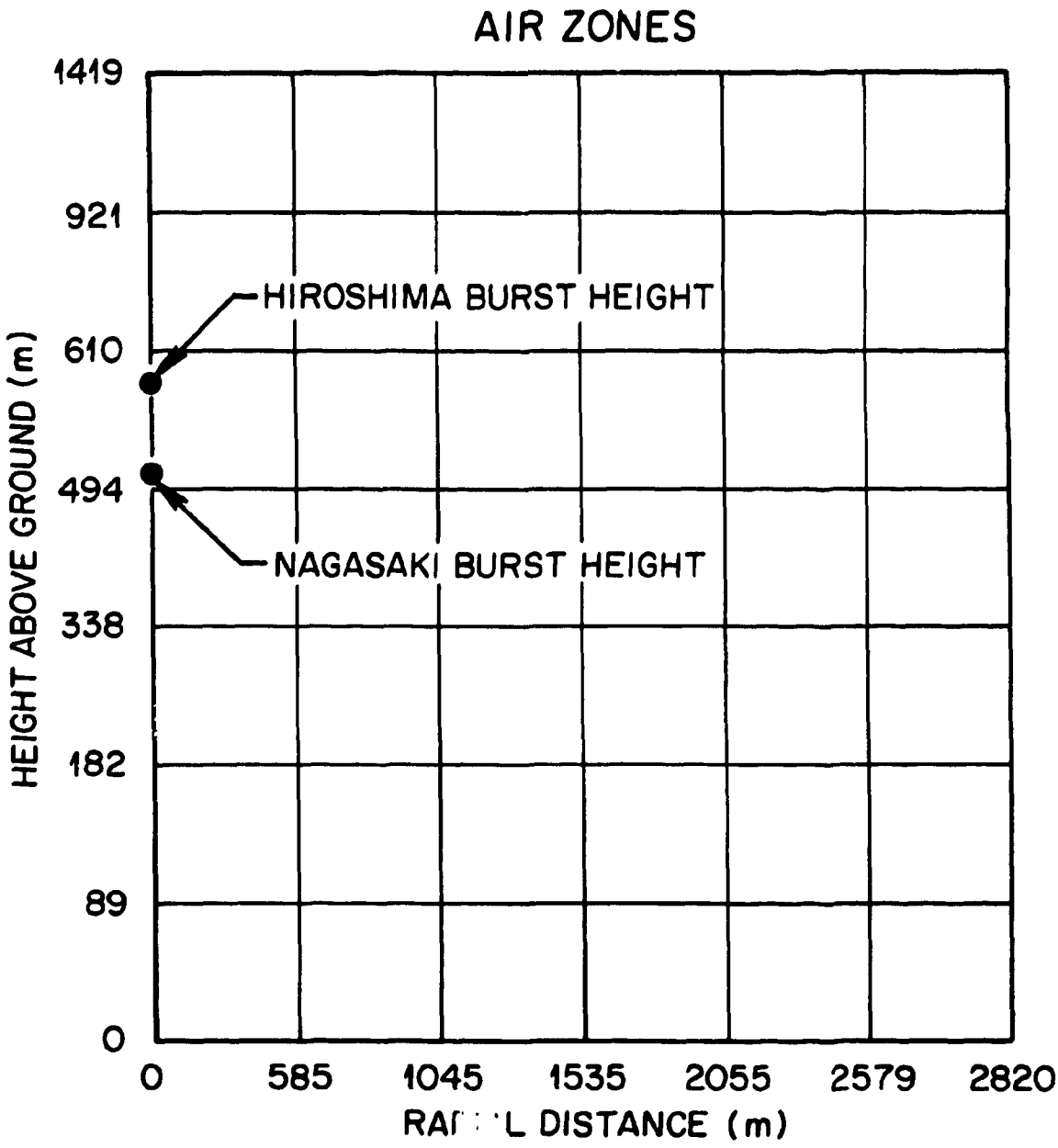

Fig. 10. Schematic illustrating the air zones used in the cylindrical air-over-ground geometry of the two-dimensional calculations with the DOT-IV code.

energy spectrum changes rapidly with distance. The energy spectrum of prompt neutrons became invariant or reached an equilibrium at an air-penetration distance of several hundred meters in Nagasaki, but in Hiroshima, the air-penetration distance was nearly 2000 m before the energy spectrum of prompt neutrons reached an equilibrium state.[16,17]

An anomaly known as the ray effect occurs in two-dimensional DOT calculations using a cylindrical air-over-ground geometry if the size of the source and detector are small, the scattering mean-free path is large compared with the space mesh, and portions of the space mesh are not intersected by at least one of the discrete polar angles.[16,17] If ray effects are dominant, then the particle fluences will be too large in space meshes which are intersected by the discrete polar angles and too small in those which are not. This effect can be mitigated: (a) by using the first-collision source method, which moderates the rays by placing an analytic first-collsion source in each space mesh, or (b) by using a higher angular quadrature (i.e., more polar angles). For most cases, the first method will ensure accurate results. However, if the small or point source in turn produces another localized source (e.g., secondary gamma production) which appears as another point source, then a combination of both a first-collision source and a higher order angular quadrature must be used to obtain the proper particle fluences.

After the first-collision source was obtained from input of the appropriate particle source[24,25] and cross sections, the total collided-particle fluence was calculated with the DOT-IV code.[14,15] Any calculations that required a higher order angular quadrature in

addition to a first-collision source were first run with a low-order angular quadrature (i.e., 48 polar angles) until convergence was obtained and were then restarted with a higher order angular quadrature (i.e., 240 polar angles) until convergence was again obtained (usually after one more iteration). The final results (uncollided plus collided-particle fluence) were then convoluted with response factors (e.g., in-air tissue kerma and sulfur activation) available in the standard DNA energy-group structure.[65]

SULFUR ACTIVATION

A new investigation which takes into account both the anisotropy of the neutron leakage from the Hiroshima device[24] and the shielding of sulfur by the porcelain insulators[70] has been completed (see Figs. 11 and 12). The dimensions of the porcelain insulators were taken from work by Tajima and Oda,[70] and the density and composition of porcelain (i.e., 2.6 g cm^{-3} and $Al_2O_2 + 2SiO_2 + 2H_2O$) were taken from work by Sugimoto.[71] Additional information concerning methods of mounting the porcelain insulators on electric poles was provided by A. A. Thibaut, Technical Consultant to the Bureau of Power, Knoxville Utilities Board.[72] The most likely method was a steel pin covered with a lead sleeve (see Fig. 13). Our adjoint DOT-IV calculations of the shielding of sulfur by the porcelain insulators also considered two other potential mounting methods: a steel pin only, and a wood pin only (i.e., no lead sleeve). These various mounting methods were found to have a negligible effect (i.e., less than a 2% difference) on the neutron activation of sulfur used as an adhesive material in mounting the porcelain insulators on electric poles.

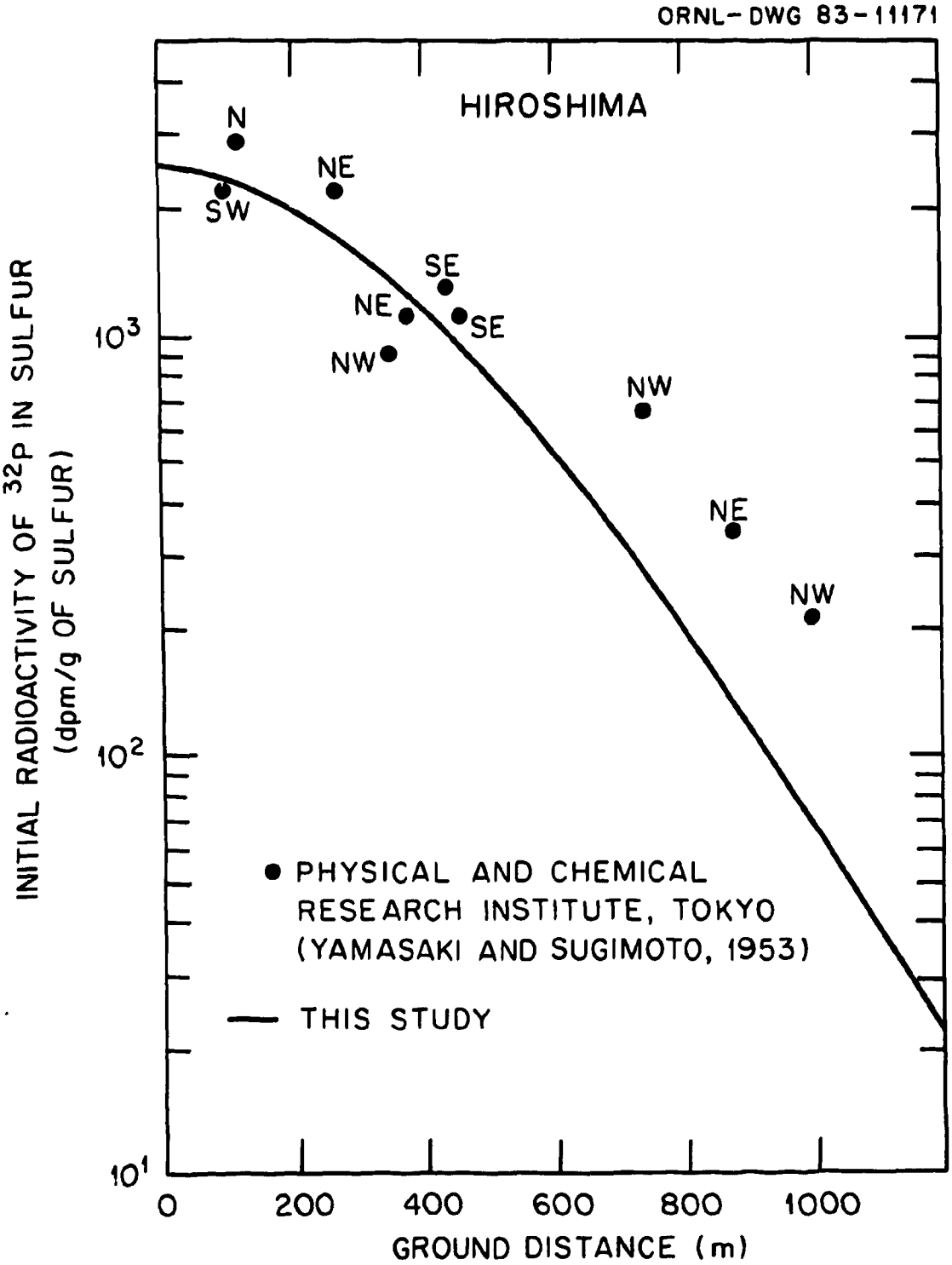

Fig. 11. Comparison of theoretical and experimental data on sulfur activation in Hiroshima. The direction with respect to the hypocenter is indicated for each experimental data point.

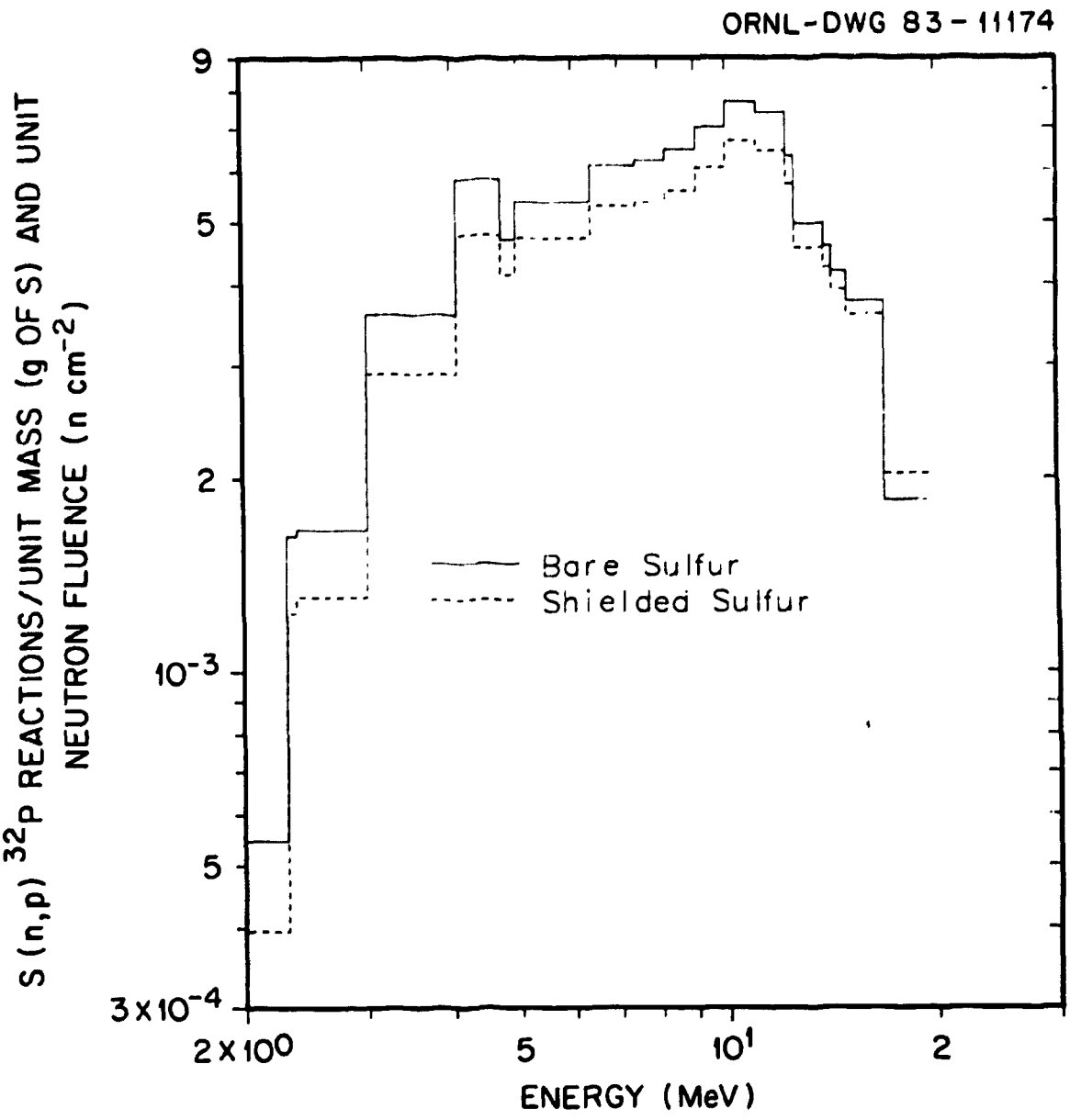

Fig. 12. Energy dependent-response functions for neutron activation of bare sulfur and of sulfur shielded by porcelain insulators on electric poles. Since the exact orientation of the insulators is unknown, it was assumed that the neutrons were incident isotropically.

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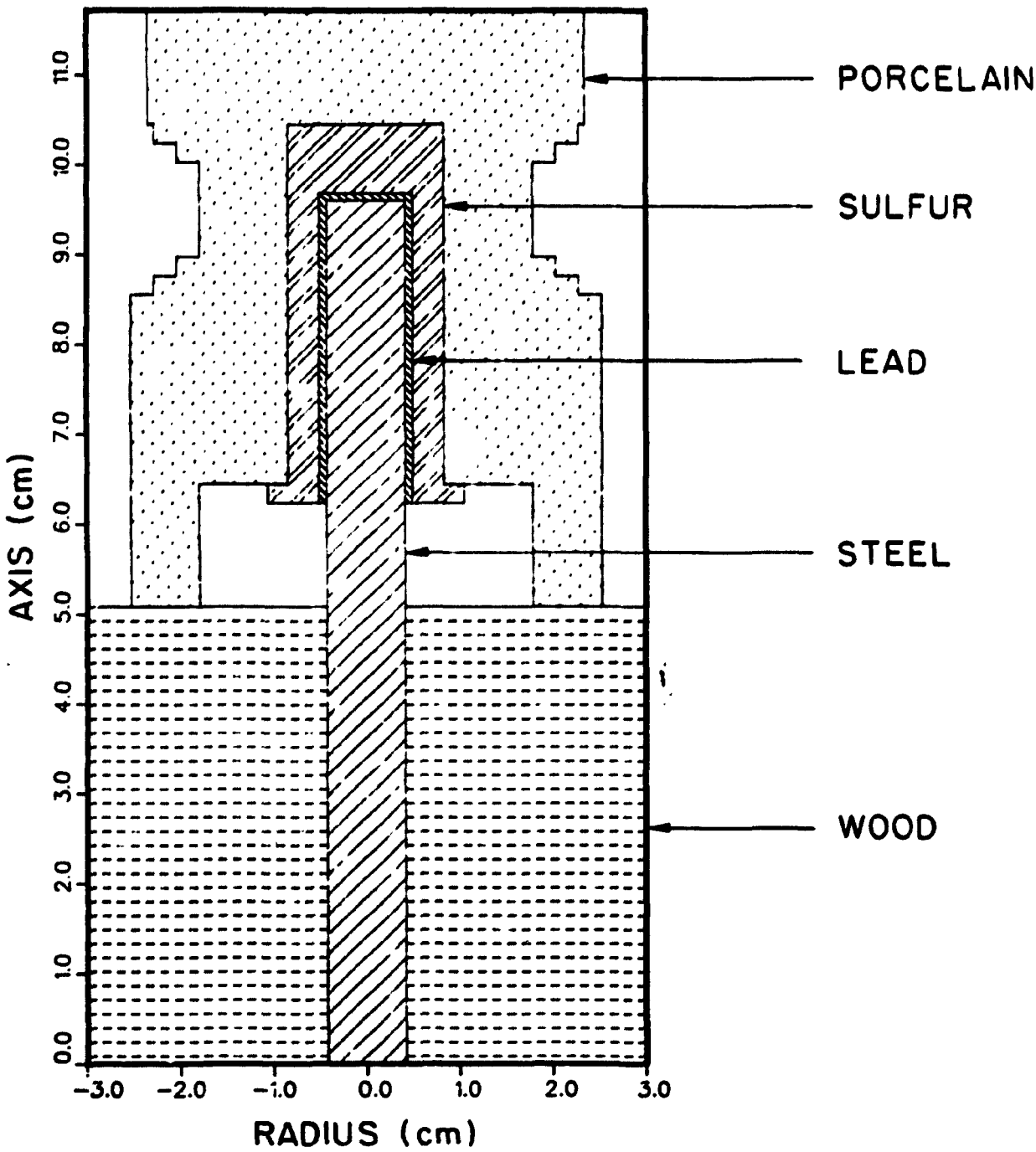

Fig. 13. Schematic illustrating the most likely method used in mounting porcelain insulators on electric poles in Hiroshima.

The most detailed and widely referenced set of data on [illegible] activation in Hiroshima comes from measurements made in 1945 by the Physical and Chemical Research Institute in Tokyo.[59,62,73] Their measurements were made using one-gram samples of sulfur and a Lauritsen electroscope which had been calibrated with a one-gram source of uranium oxide. The comparisons of this report use experimental values from the 1953 report by Yamasaki and Sugimoto.[59] Later work, taking into account differences between older and newer data on the decay constant of uranium (i.e., ^{238}U) and differences between the beta-particle spectra of uranium (i.e., ^{234m}Pa) and ^{32}P, suggests that the original values should be revised upward by factors ranging from 1.09 to 1.36 (Ref. 74).

We have not been able to find any equivalent data from sulfur-activation measurements in Nagasaki. However, a relative value for neutron activation of sulfur in the two cities is given in a 1953 report by Miyazaki and Masuda.[75] Their report states: "The intensity of radiation (from neutron activation of the ground) about the hypocenter is approximately 45 J (where 1 J is equal to one ion-pair s^{-1} cm^{-3} of air under standard conditions or an in-air tissue kerma rate of about 17.5 pGy hr^{-1}) both in Nagasaki and Hiroshima (about six months after the bombings). According to Motoharu Kimura, the intensity of radiophosphorus caused by slow (or thermal) neutrons in Hiroshima was four times that in Nagasaki, while the intensity of radioactive sulfur caused by fast neutrons at Nagasaki was 1.6 times higher than at Hiroshima. Therefore, the cause of the intensity of radiation about the hypocenters has not been explained yet." Our theoretical values also indicate that sulfur

activation was greater in Nagasaki than in Hiroshima by factors varying from about 3 at the hypocenters to about 1.5 at ground distances of 1000 m (see Table 12).

The excellent agreement between the theoretical and experimental data on sulfur activation, especially at small ground distances in Hiroshima where the experimental data are considered to be the most reliable, is gratifying (see Fig. 11). However, the theoretical values for sulfur activation in Hiroshima are still considered preliminary. Due to the cylindrical air-over-ground geometry used in the two-dimensional DOT-IV calculations, the Hiroshima device had to be oriented along the vertical Z-axis (see Fig. 10) with the blind spot in the neutron leakage through its nose section pointed directly downward toward the ground (see the 0^{o} angle in Figs. 7 and 9). It has been suggested by both Kerr[19-21] and Malik[76] that the Hiroshima device was probably tilted about 15^{o} with respect to the vertical at the time of explosion. Since the direction of the approach of the bombing and observation aircraft was from ENE toward WSW (Ref. 40) (see Fig. 14), the nose of the Hiroshima device would have been pointed at a ground location about 150 m WSW of the hypocenter. A complex three-dimensional Monte Carlo calculation of the directional dependence of sulfur activation due to the probable tilt of the Hiroshima device at the time of explosion is needed before the theoretical values can be considered final. The Nagasaki device was also probably tilted at about 15^{o} with respect to the vertical at the time of explosion, but it was a spherically symmetric device with a nearly isotropic neutron leakage (see Fig. 8).

Table 12. Comparison of theoretical values for neutron activation of sulfur shielded by porcelain insulators mounted on electric poles in Hiroshima and Nagasaki

Ground distance (m)	Initial radioactivity of ^{32}P in sulfur (dpm per g of S)		Nagasaki to Hiroshima ratio
	Hiroshima	Nagasaki	
98.25	2.59E+3[a]	7.79E+3[a]	3.01
215	1.95E+3	5.39E+3	2.76
305	1.57E+3	3.94E+3	2.51
395	1.19E+3	2.72E+3	2.29
500	8.23E+2	1.68E+3	2.04
610	5.00E+2	9.02E+2	1.80
700	3.22E+2	5.43E+2	1.69
790	2.03E+2	3.25E+2	1.60
910	1.07E+2	1.63E+2	1.52
1000	6.55E+1	9.67E+2	1.48

[a]Based on energy yields of 12.5 and 22 kt for the Hiroshima and Nagasaki explosions, respectively. The above theoretical values were obtained by convoluting data on fluence and energy spectra of neutrons from our DOT-IV calculations at the given ground distances with energy dependent-response functions from adjoint DOT-IV calculations for neutron activation of sulfur shielded by porcelain insulators mounted on a steel pin with a lead sleeve as shown in Fig. 13. Since the exact orientations of the insulators was unknown, it was assumed that the neutrons were incident isotropically.

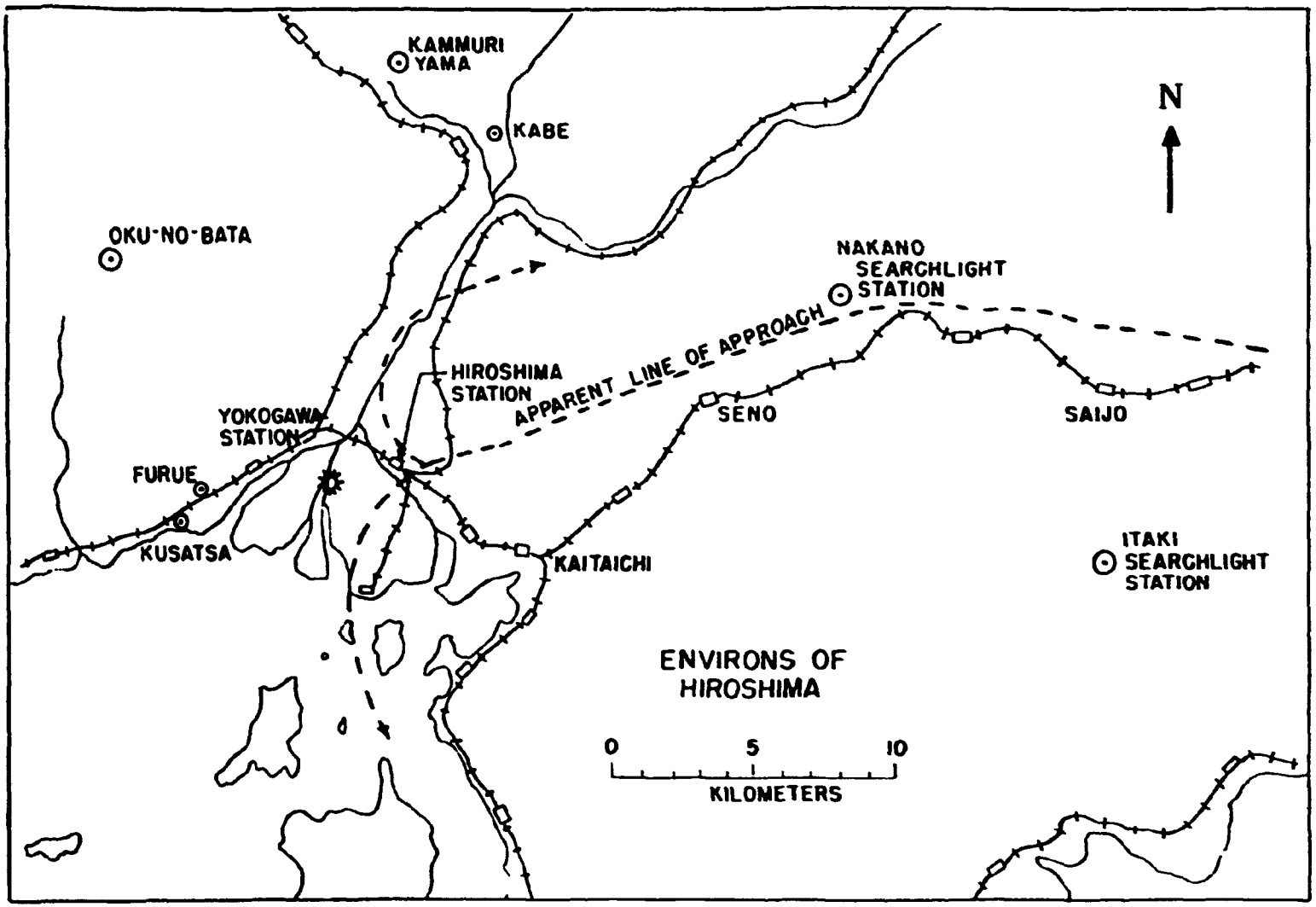

Fig. 14. Map showing environs of Hiroshima and direction of approach of the bombing and observation aircraft (Ref. 40). The bombing aircraft turned north after releasing the bomb, and the observation aircraft turned south after releasing three parachute-retarded canisters to record the air pressure during the explosion.

TRANSPORT OF DELAYED INITIAL NUCLEAR RADIATION

Transport of delayed initial nuclear radiation in Hiroshima and Nagasaki has been estimated using the NUIDEA code.[27,28] The modeling of the transport of delayed initial nuclear radiation in NUIDEA takes into account the fission-product isotopes, their radioactive decay, the reduction in the amount of air between the source and a detector at ground level by the shock wave, and, finally, the rising of the low-density well or bubble of very high-temperature gases contained in the fireball. The NUIDEA code[26] uses the Low Altitude Multiple Burst (or LAMB) model[77] for scaling to the desired energy yield, burst height, and ground distance. The LAMB model is a synthesis of hydrodynamic calculations with a one-dimensional shock-wave form and an image burst source for reflection of the shock wave by the ground. The fireball modeling in LAMB includes a low density well, bouyancy, air drag, reflected shock impulse, and torus formation. Of course, the effects of reflected shock impulse on fireball rise and on torus formation in the fireball are less important in applications to the high altitude bursts in Hiroshima and Nagasaki.

Previous studies at SAI have shown that comparisons between NUIDEA and the best available time-dependent data from weapon tests were improved when the source data for the fission-product gammas was updated to include the fraction of original fissioning isotopes (i.e., ^{235}U, ^{238}U, and ^{239}Pu). Differences of 20 to 30% were typical with the theoretical values being low compared to the experimental values. These differences were attributed primarily to a lack of information on the very early-time decay of fission products in the

fireball. The source data and the LAMB model have been reexamined in more recent studies.[78] For example, another version of the LAMB model, called STLAMB, was obtained from D. Dean of the McDonnell Douglas Corporation.[79] STLAMB is similar to LAMB except it contains some differences in the modeling of the fireball density well and in the treatment of the fireball rise. The source data were investigated with both LAMB models, and the results were compared with three weapon tests (i.e., Hood, Wilson, and Owens) from the Operation Plumbbob series.[80] One LAMB model could not be identified as preferable to the other model. The comparisons gave us confidence, however, that the LAMB models provide an adequate method for scaling data from weapon test measurements to the energy yields, burst heights, and air densities of the Hiroshima and Nagasaki explosions.

Three sets of source data for fission-product gammas were examined. The first set designated as ISO was the ENDF/B-IV spectra[81] which were used in our earlier work. These source data give results which are systematically low by 20 to 30% especially at the larger ground distances (see Table 13). The second set designated as FE was an approximation of the spectra of fission-product gammas measured in 1964 by Fisher and Engles.[82] SAI's more recent work uses the following exponential fit to the energy dependence of the Fisher and Engles measurements for times between about 0.1 and 30 seconds (see Table 14):

$$S(E,t) = N \frac{R(t)}{E_{avg}(t)} \exp\left[-E/E_{avg}(t)\right] , \qquad (3)$$

Table 13. Comparison of data on tissue kerma from delayed fission product gammas[a]

Ground distance (m)	In-air tissue kerma (Gy)			
	Experimental	NUIDEA/ISO	NUIDEA/FE	NUIDEA/WT
Shot Hood (burst height = 456 m, energy yield = 71 kt)				
915	4.3E+1	4.4E+1 (+ 2%)[b]	5.5E+1 (+28%)[b]	4.9E+1 (+14%)[b]
1371	7.3E+0	5.1E+0 (-30%)	8.1E+0 (+11%)	6.9E+0 (- 5%)
2284	2.3E-1	1.3E-1 (-43%)	2.5E-1 (+ 9%)	2.0E-1 (-13%)
2779	3.8E-2	2.7E-2 (-29%)	4.8E-2 (+26%)	3.8E-1 (0%)
3272	7.8E-3	6.0E-3 (-23%)	1.0E-2 (+28%)	7.7E-3 (- 1%)
Shot Owens (burst height = 152 m, energy yield = 9.7 kt)				
457	6.7E+1	5.9E+1 (-65%)	9.1E+1 (+36%)	6.0E+1 (-10%)
915	5.3E+0	3.9E+0 (-25%)	7.6E+0 (+43%)	4.6E+0 (-13%)
1370	5.0E-1	4.1E-1 (-18%)	8.6E-1 (+72%)	4.9E-1 (- 2%)
1829	7.2E-2	5.5E-2 (-24%)	1.2E-1 (+67%)	6.4E-2 (-11%)
2285	1.4E-2	1.0E-2 (-29%)	2.1E-2 (+41%)	1.0E-2 (-29%)
2779	2.2E-3	1.9E-3 (-14%)	3.5E-3 (+59%)	1.7E-3 (-23%)
Shot Wilson (burst height = 152 m, energy yield = 10 kt)				
457	1.1E+2	7.8E+1 (-29%)	1.1E+2 (0%)	8.6E+1 (-22%)
915	6.5E+0	4.9E+0 (-23%)	8.9E+0 (+37%)	6.9E+0 (-13%)
1370	5.7E-1	4.9E-1 (-14%)	1.1E+0 (+93%)	7.7E-1 (+35%)
2285	1.5E-2	1.1E-2 (-27%)	2.6E-2 (+73%)	1.8E-2 (+20%)

[a]Scott (Ref. 78).

[b]100 x (theoretical value - experimental value)/experimental value.

Table 14. Empirical source parameters for delayed fission-product gammas derived from laboratory measurements of Fisher and Engles (FE) and field measurements at the Operation Plumbbob series of weapon tests (WT)

Empirical parameter[a]	Fisher and Engles (FE)	Weapon tests (WT)
Source normalization factor, N:[b]		
^{235}U	0.7	0.7
^{239}Pu	0.5	0.5
^{238}U	1.5	
Average gamma energy, $E_{avg}(t)$:[c]		
^{235}U	0.94 MeV ($t < 2$ s) 0.91 MeV ($t > 4$ s)	0.93 MeV ($t < 2$ s) 0.82 MeV ($t > 3$ s)
^{239}Pu	0.86 MeV ($t < 2$ s) 0.83 MeV ($t > 4$ s)	0.815 MeV ($t < 1$ s) 0.74 MeV ($t > 2$ s)
^{238}U	0.95 MeV ($t < 1$ s) 0.89 MeV ($t > 4$ s)	

[a]Scott (Ref. 78).

[b]The source normalization reflects the differences in the intensity of the fission product gammas emitted by the various fissionable isotopes.

[c]The average gamma energy at other times within the indicated time limits was obtained by linear interpolation.

where the emission rate in photons per sec per fission, R(t), is

$$R(t) = 0.8/(1 + 0.8\ t) \qquad (4)$$

for either ^{235}U or ^{239}Pu, and

$$R(t) = 0.8/(1 + 0.92\ t + 0.43\ t^2) \qquad (5)$$

for ^{238}U. These source data were found to be systematically high by about 30 to 70% at the larger ground distances (see Table 13). The third set designated as WT was developed from weapon test data (see Table 14) by the use of modified energy spectra with the same time dependency as the Fisher and Engles measurements (see Eqs. 3-5).

Fifteen time-dependent measurements of delayed fission-product gammas were made during the Hood, Owens, and Wilson Shots of Operation Plumbbob series. Shots Owens and Wilson have energy yields comparable with those of the Hiroshima and Nagasaki explosions, and Shot Hood has a comparable burst height. The WT set of source data is an approximation developed within our knowledge of the early time decay spectra of fission-product gammas[81-86] to give the best time- and distance-agreement with fifteen of the field measurements from the Operation Plumbbob series. Comparisons of experimental and theoretical data at two ground distances from Shot Hood are shown in Figs. 15 and 16. On each figure, five time-dependent curves are plotted: the first is the experimental data,[80] and the last is from a model developed in 1966 by Loewe et al.[87] The other three are from our studies. All total tissue-kerma values are time integrals for the delayed fission-product gammas and do not include prompt primary or secondary gammas. The experimental tissue-kerma values were obtained by integration

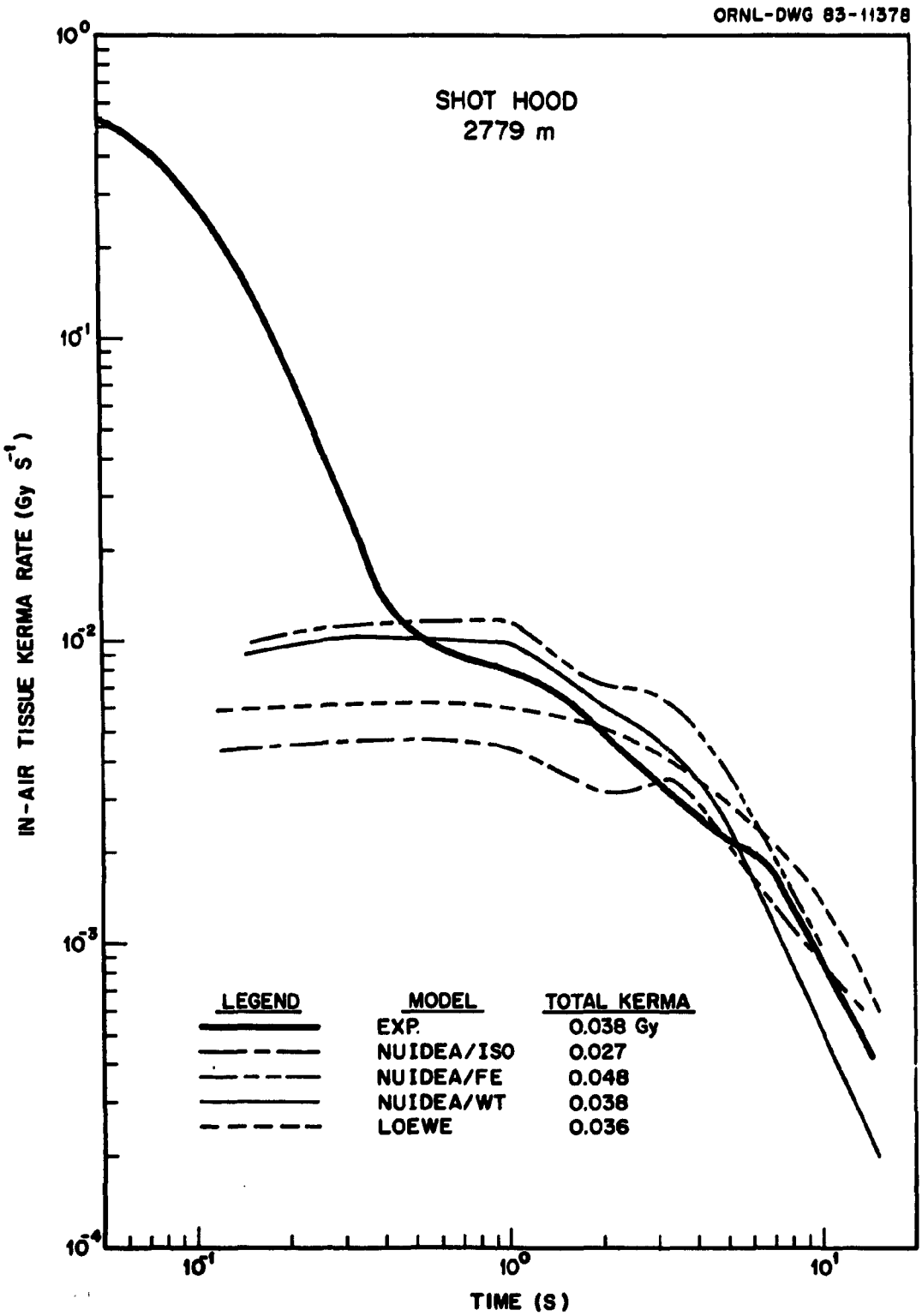

Fig. 15. In-air tissue kerma rate from delayed fission-product gammas as measured and calculated for Shot Hood at a far ground distance of 2779 m (Ref. 27,78).

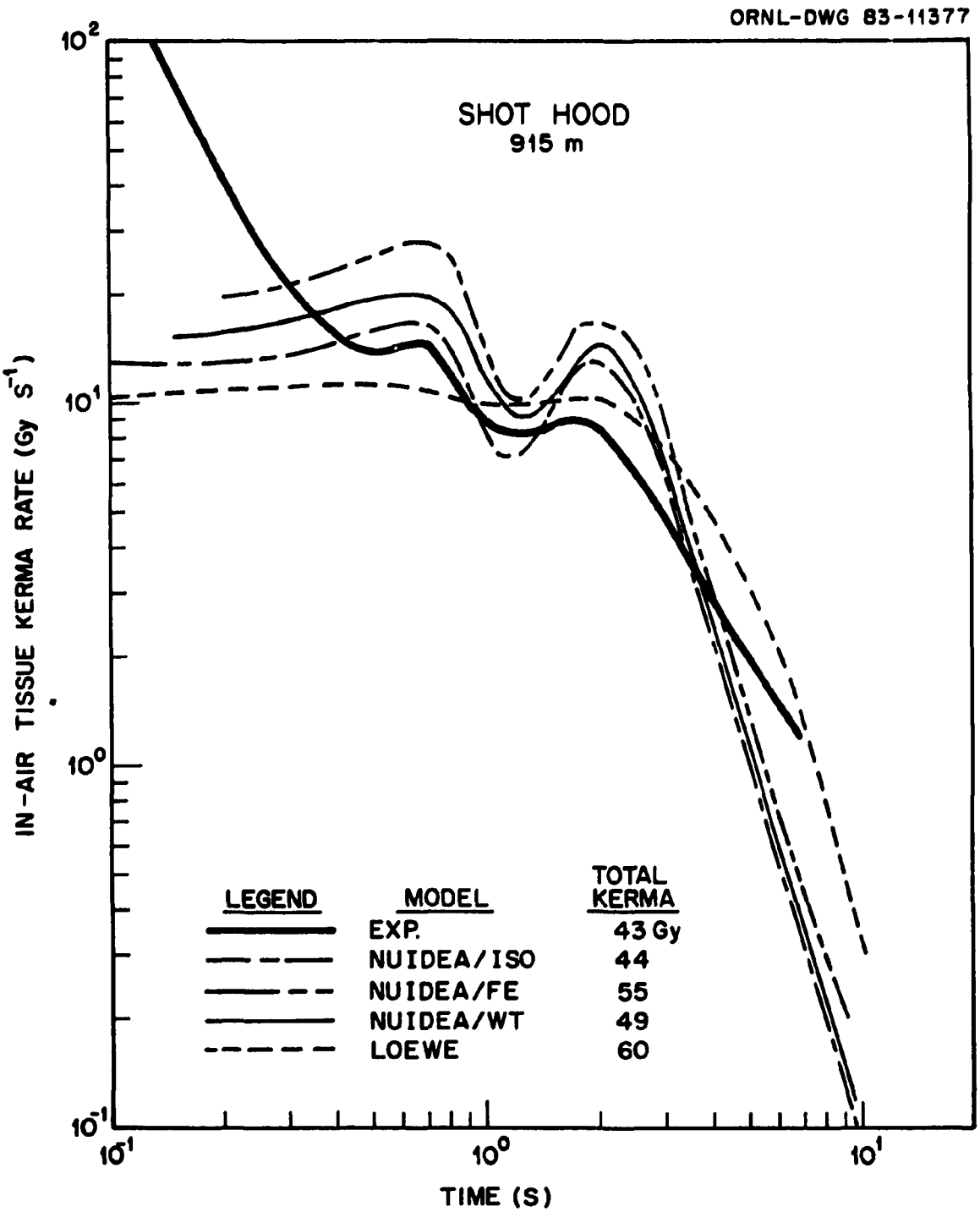

Fig. 16. In-air tissue kerma rate from delayed fission-product gammas as measured and calculated for Shot Hood at a close ground distance of 915 m (Ref. 27,78).

after subtracting out an exponential time-dependent fit to the prompt secondary gammas which arrived at times less than 0.5 second.

One significant uncertainity which still remains is the contribution from ^{238}U fissions in the Nagasaki device. Only about 20% of the Nagasaki fissions occurred in ^{238}U; however, they contributed nearly half of the tissue kerma from delayed fission-product gammas. Since the field measurements contained no substantial contribution from ^{238}U, and there are no recent laboratory measurements of the ^{238}U early time spectrum, a source normalization derived from the ENDF/B-IV data[81] and the Fisher-Engle measurements[82] was used. SAI's continued examination of source data for ^{238}U may cause a later revision in current estimates of tissue kerma from the delayed fission-product gammas in Nagasaki.

RESULTS AND DISCUSSION

Results of our state-of-the-art calculations have been summed to obtain the total in-air tissue kerma from gammas in Hiroshima and Nagasaki as shown in Figs. 17 and 18. The components for the prompt and delayed gammas in Hiroshima are noticeably different from those reported in our 1981 work.[17,19-21,27] Our latest NUIDEA/WT estimates of in-air tissue kerma from delayed fisson-product gammas are larger by as much as 30% compared to our earlier NUIDEA/ISO estimates, and our latest estimates of in-air tissue kerma from prompt primary and secondary gammas are smaller than our earlier estimates. The decrease in prompt secondary gammas (and prompt primary gammas) in Hiroshima is due to differences in the spectrum and number of source leakage neutrons (and gammas) between the 1975 one-dimensional

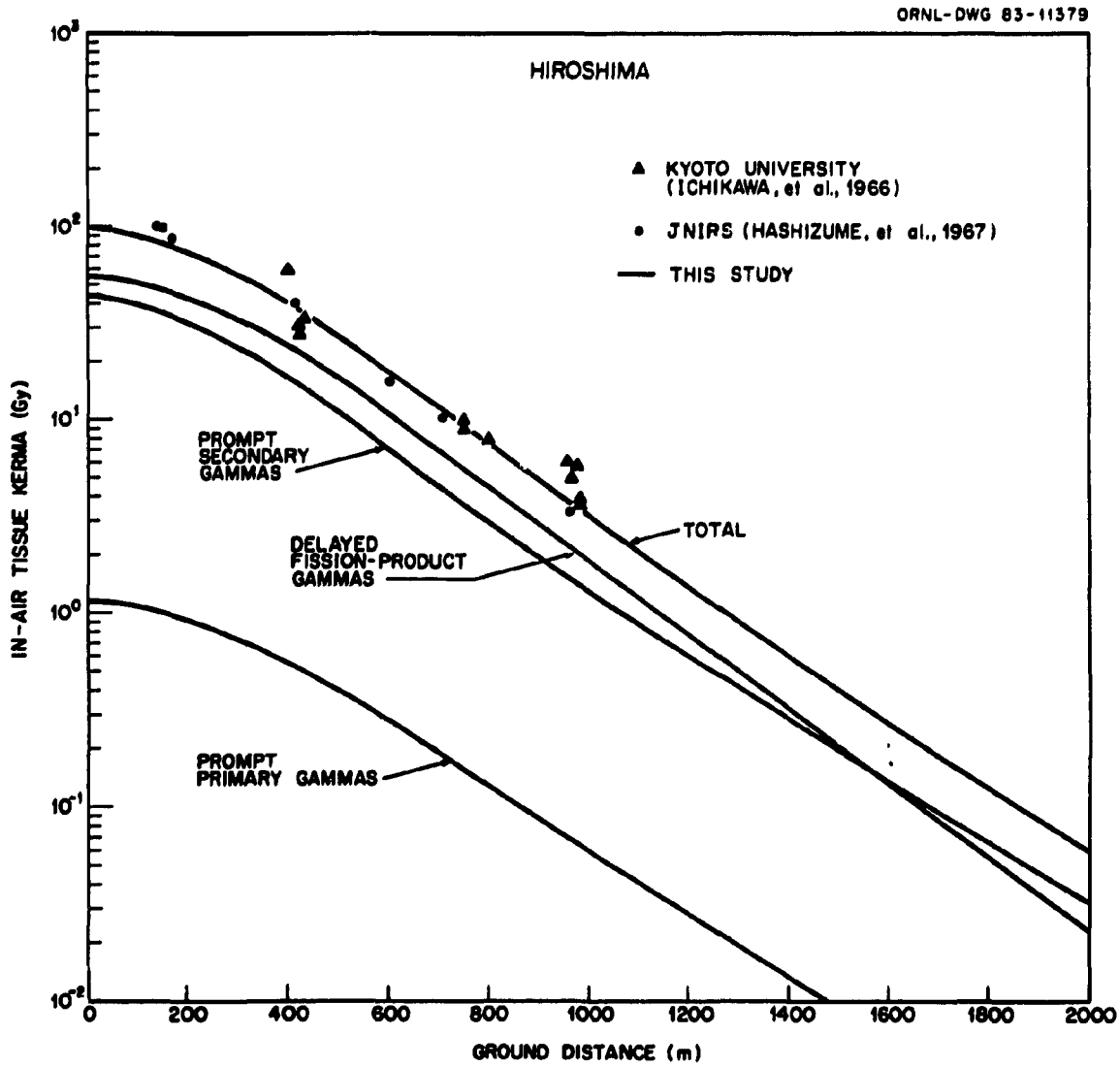

Fig. 17. Comparison of values from thermoluminescent measurements by Ichikawa et al. (Ref. 88) and Hashizume et al. (Ref. 91) and from state-of-the-art calculations for the gamma component of initial nuclear radiation in Hiroshima.

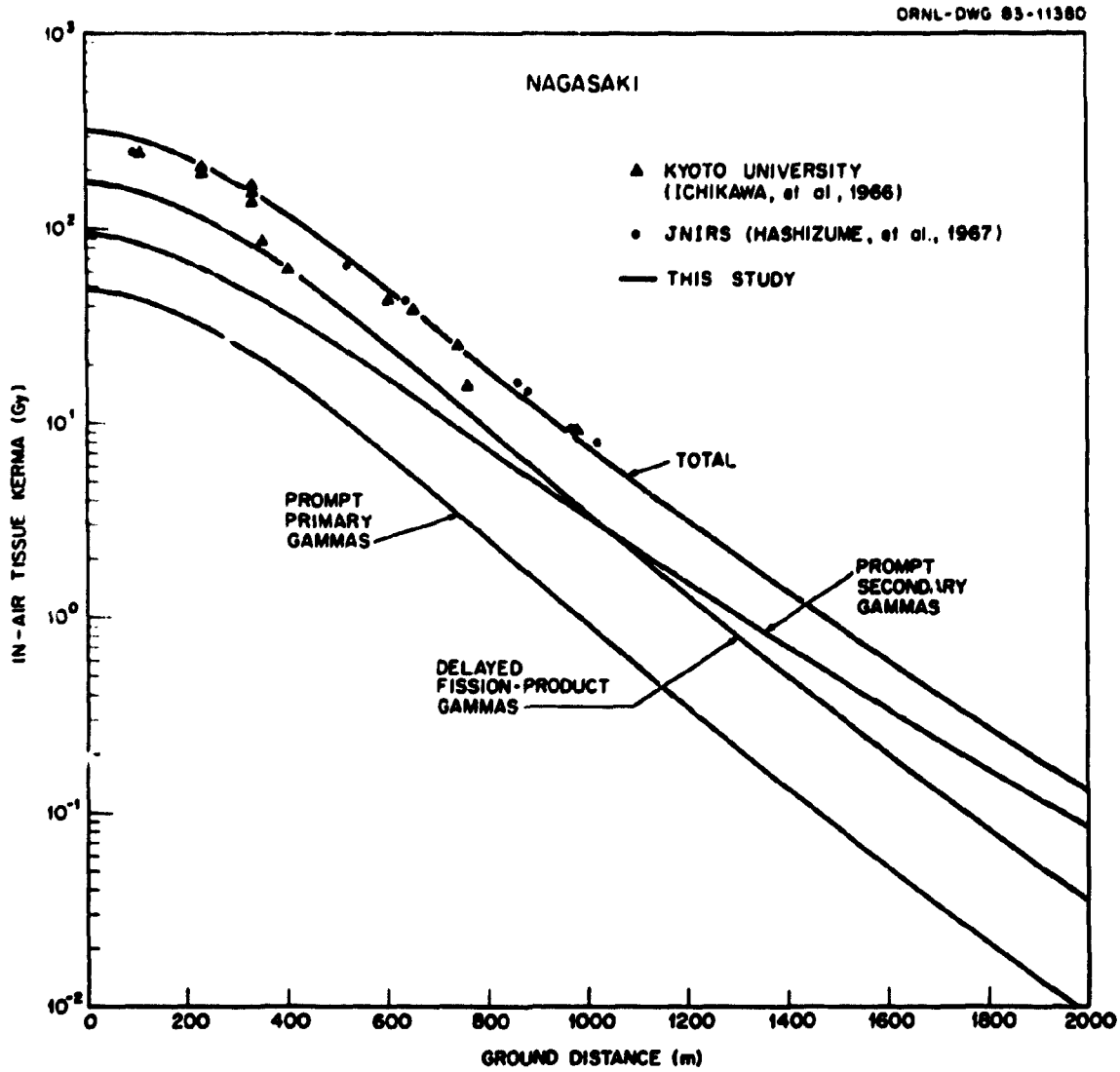

Fig. 18. Comparison of values from thermoluminescent measurements by Ichikawa *et al.* (Ref. 88) and Hashizume *et al.* (Ref. 91) and from state-of-the-art calculations for the gamma component of initial nuclear radiation in Nagasaki.

calculations by Preeg[18] and the 1982 two-dimensional calculations by Whalen.[24] For example, Whalen's value for the number of source leakage neutrons is about 15% less than Preeg's value (see Table 11). The compensating differences in the various components for prompt and delayed gammas give essentially the same total in-air tissue kerma from gammas in Hiroshima as our earlier 1981 work.[19-21,27]

Experimental measurements of gamma-induced thermoluminescence in various ceramic materials in Hiroshima and Nagasaki have been reported by Ichikawa et al. of Kyoto University[88,89] and by Hashizume et al. of the Japanese National Institute of Radiological Sciences (JNIRS) (Ref. 90,91). Ichikawa and his colleagues[89] estimated the gamma exposure at various ground distances in Hiroshima and Nagasaki by using thermoluminescence of the crystalline component from roof tiles. Some rather large uncertainties were involved in the distance estimates of their study, however.[91] Since roof tiles were used only on Japanese houses and all houses close to the hypocenter were destroyed, the exact location of each roof-tile sample ATB was in doubt. The estimates of gamma exposure by Hashizume et al.[91] were derived from measurements of gamma-induced thermoluminescence in decorative-tile and brick samples from buildings that had been repaired and used for a number of years after the bombings. Thus, the exact location of each sample ATB was well known, and the uncertainty in the ground distance was minimized. The JNIRS experimental values and our theoretical values for the total in-air tissue kerma agree to within about 10% in both cities (see Figs. 17 and 18).

Results of our state-of-the-art calculations for both gamma rays and neutrons are further compared with the tentative 1965 dose (or

T65D) estimates[35,92-95] in Figs. 19 and 20. In-air tissue kerma from neutrons in both cities are lower than the T65D estimates. The observed differences are, however, the most dramatic in Hiroshima. In Hiroshima, our latest estimates for in-air tissue kerma are lower than the T65D estimates by factors of 10 or more at ground distances greater than 1000 m, and our latest estimates of the tissue kerma from gammas are greater than the T65D estimates starting at a ground distance of about 1000 m and are larger by a factor of about 3 at 2000 m (see Fig. 19). In Nagasaki, the situation is reversed with respect to in-air tissue kerma from gammas, and the T65D estimates are higher (see Fig. 20), but the differences are small (i.e., about 15% at a ground distance of 1000 m and 30% at 2000 m).

Several significant uncertainties in our latest results are the lack of any reliable estimate of the in-air tissue kerma from delayed neutrons for either city, the magnitude of the ^{238}U contribution to in-air tissue kerma from delayed fission-product gammas in Nagasaki, and the magnitude of the energy yield of the Hiroshima explosion. We use the T65D value of 12.5 kt,[33-35] Loewe and Mendelsohn[66-68] use 15 kt, and Malik[76] suggests 17 kt. These various uncertainties are currently being investigated by several national laboratories and consulting firms within the U.S. We hope that answers to these and other remaining questions concerning the reassessment of A-bomb radiation dosimetry will soon be provided by the joint studies within the U.S. and Japan.

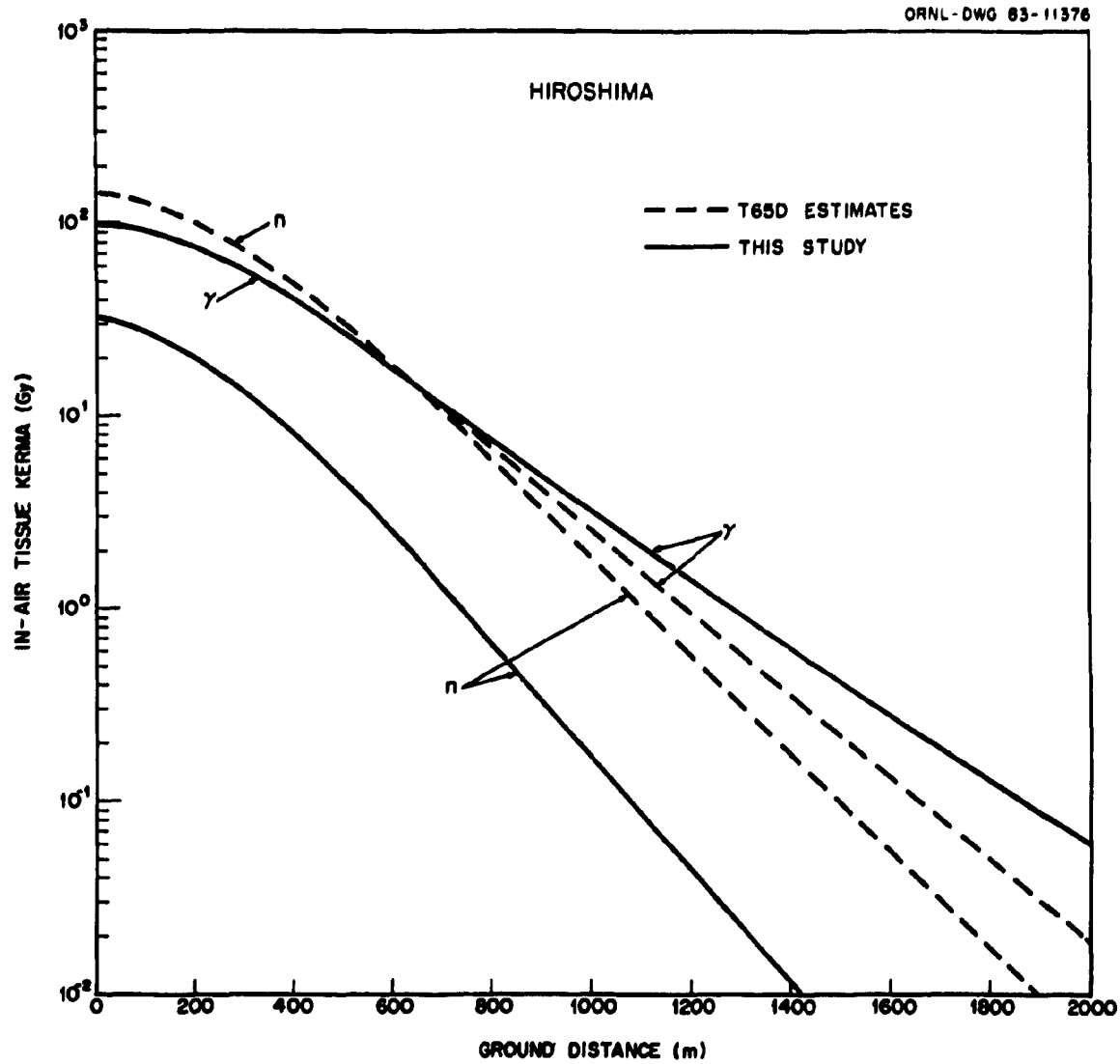

Fig. 19. Comparison of values from the Tentative 1965 Dose (or T65D) study (Ref. 35,95) and from state-of-the-art calculations for initial nuclear radiation in Hiroshima.

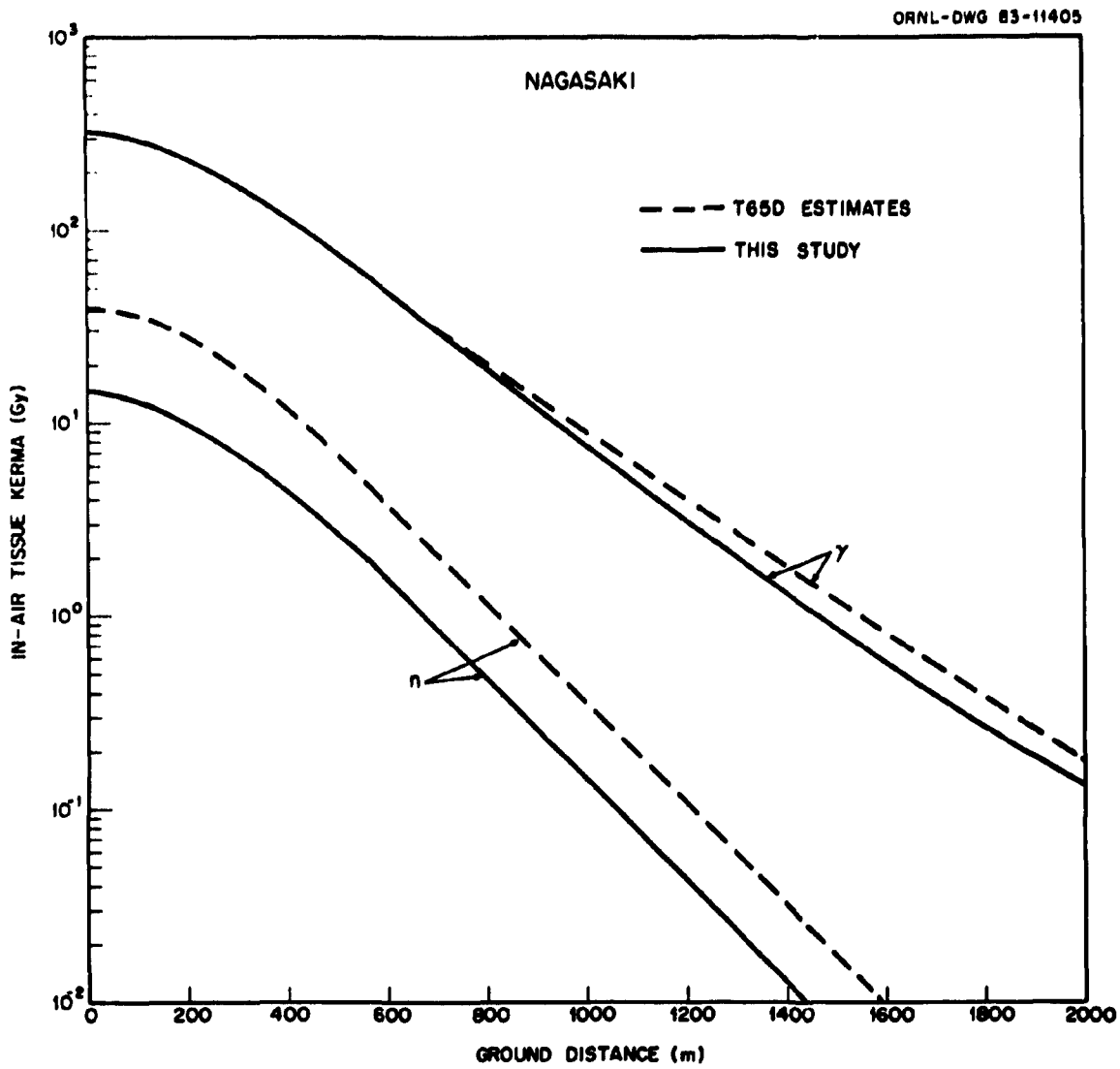

Fig. 20. Comparison of values from the Tentative 1965 Dose (or T65D) study (Ref. 35,95) and from state-of-the-art calculations for initial nuclear radiation in Nagasaki.

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APPENDIX A

Weather aloft over Southern Japan on 5, 6, and 9 August 1945

Weather conditions aloft over Southern Japan at the times of the bombings (ATB) in Hiroshima and Nagasaki are summarized in Tables A1, A2, and A3. These data are from the 1946 collection by Castles[1] of the U.S. Strategic Bombing Survey in Japan.[2,3] Table A3 gives data on wind velocities aloft at Tokyo on 6 August 1945 at 1000 hours and 9 August 1945 at 1400 hours. These data were previously discussed by Auxier et al.[4] Tables A1 and A2 give data on temperature, pressure, and humidity as functions of altitude from radiosonde measurements made over Fukuoka on 5 August 1945 at 2200 hours, Toyohasi on 6 August 1945 at 2200 hours, and Tokyo on 6 and 9 August 1945 at 0600, 1000, 1400, 1800, and 2200 hours.

The mixing ratio, w, defined as the ratio of the mass of water vapor to the mass of dry air in a specified volume,[5,6] was calculated by using the equation:

$$w = 0.611\ U\ e_s/(P - U\ e_s)\ , \qquad (A1)$$

where P is pressure in millibars (or mb), U is relative humidity, and e_s is water vapor pressure in mb of saturated air. Values for e_s were taken from the CRC Handbook of Chemistry and Physics.[7] The mixing ratio calculated by the above equation was multiplied by 1×10^6 to obtain a unit of parts per million (or ppm) by mass.

Several empirical constants were derived as follows from the data in Tables A1 and A2. First, a constant temperature lapse rate in the troposphere was assumed as in the model of the U.S. Standard Atmosphere,[4,6,7] and a value of 5.8 °K km^{-1} with a standard deviation of about 0.2 °K km^{-1} was obtained by applying the method of least squares to the pooled data on temperature vs altitude between

Table A1. Weather aloft over Southern Japan on 5 and 6 August 1945

Altitude (m)	Pressure (mm)	Temperature (°C)	Humidity (%)	Mixing ratio (ppm)
Fukuoka - August 5 - 2200 hours				
4	762	26	93	1.97E+3[a]
994	680	22	98	1.83E+3
2065	600	17	98	1.51E+3
3108	530	11	90	1.06E+3
4104	470	7	94	9.49E+2
5220	410	3	93	8.13E+2
6044	370	-2	92	6.18E+2
7184	320	-8	82	4.03E+2
8205	280	-16	74	1.87E+2
9042	250	-24	64	8.39E+1
10293	210	-33	61	3.79E+1
Tokyo - August 6 - 0600 hours				
43	760	23	99	1.76E+3
1007	680	23	97	1.93E+3
2085	600	20	70	1.30E+3
3139	530	16	37	5.98E+2
4149	470	10	44	5.41E+2
5257	410	-2	45	2.66E+2
6069	370	-6	38	1.77E+2
7188	320	-11	36	1.25E+2
8266	280	-17	34	7.80E+1
9169	250	-28	31	2.71E+1
10354	210	-33	27	1.68E+1
Tokyo - August 6 - 1000 hours				
43	759	30	63	1.69E+3
1012	680	21	91	1.59E+3
2079	600	16	55	7.87E+2
3122	530	12	40	4.98E+2
4114	470	7	46	4.61E+2
5218	410	-1	46	2.96E+2
6033	370	3	39	2.35E+2
7164	320	-11	35	1.33E+2
8185	280	-17	33	8.31E+1
9032	250	-24	30	5.27E+1
10299	210	-28	28	2.91E+1

Table A1. (Cont'd.)

Altitude (m)	Pressure (mm)	Temperature (°C)	Humidity (%)	Mixing ratio (ppm)
Tokyo - August 6 - 1400 hours				
43	759	32	53	1.59E+3
1007	680	25	70	1.56E+3
2085	600	18	47	7.63E+2
3139	530	13	35	4.65E+2
4149	470	8	39	4.18E+2
5257	410	3	39	3.38E+2
6069	370	-2	33	2.20E+2
7188	320	-8	30	1.47E+2
8266	280	-14	27	9.37E+1
9169	250	-21	25	4.39E+1
10354	210	-29	22	2.07E+1
Tokyo - August 6 - 1800 hours				
43	759	27	69	1.55E+3
1012	680	25	65	1.44E+3
2079	600	22	38	7.91E+2
3122	530	16	33	5.32E+2
4114	470	10	33	4.05E+2
5218	410	2	34	2.74E+2
6033	370	-5	29	1.55E+2
7164	320	-11	28	1.08E+2
8185	280	-16	25	6.29E+1
9032	250	-19	24	5.10E+1
10299	210	-32	20	1.37E+1
Tokyo - August 6 - 2200 hours				
43	760	23	89	1.57E+3
1010	680	24	60	1.25E+3
2092	600	20	31	5.69E+2
3149	530	16	31	5.00E+2
4155	470	9	34	3.90E+2
5271	410	1	28	2.10E+2
6089	370	-4	26	1.49E+2
7210	320	-12	23	8.21E+1
8219	280	-18	23	4.80E+1
9059	250	-23	23	3.32E+1
10216	210	-31	20	1.53E+1

Table A1. (Cont'd.)

Altitude (m)	Pressure (mm)	Temperature (°C)	Humidity (%)	Mixing ratio (ppm)
Toyohasi - August 6 - 2200 hours				
15	764	22	92	1.52E+3
1002	680	21	76	1.32E+3
2076	600	19	73	1.27E+3
3133	530	16	58	9.42E+2
4136	470	9	51	5.86E+2
5252	410	8	47	5.79E+2
6079	370	1	40	3.33E+2
7223	320	-9	40	1.66E+2
8244	280	-15	34	9.39E+1
9091	250	-20	35	6.76E+1
10347	210	-32		

[a]Read as 1.97×10^3, etc.

Table A2. Weather aloft at Tokyo on 9 August 1945

Altitude (m)	Pressure (mm)	Temperature (°C)	Humidity (%)	Mixing ratio (ppm)
Tokyo - August 9 - 0600 hours				
43	756	23	93	1.65E+3[a]
962	680	23	79	1.56E+3
2044	600	22	43	8.97E+2
3105	530	16	32	5.16E+2
4108	470	8	34	3.64E+2
5216	410	0	33	2.30E+2
6031	370	-4	28	1.61E+2
7162	320	-10	25	1.05E+2
8183	280	-15	23	7.35E+1
9030	250	-20	22	4.25E+1
10302	210	-28	21	2.18E+1
Tokyo - August 9 - 1000 hours				
43	738	24	82	1.54E+3
750	680	19	76	1.17E+3
1817	600	17	41	6.24E+2
2863	530	13	32	4.25E+2
3855	470	5	31	2.70E+2
4951	410	-2	25	1.50E+2
5760	370	-6	20	9.87E+1
6883	320	-11	18	6.96E+1
7892	280	-19	16	3.04E+1
8729	250	-23	15	2.17E+1
9980	210	-32	13	8.93E+0
Tokyo - August 9 - 1400 hours				
43	755	32	46	1.38E+3
956	680	22	59	1.09E+3
2030	600	18	39	6.32E+2
3080	530	14	28	3.96E+2
4076	470	6	28	2.61E+2
5180	410	-1	27	1.75E+2
5992	370	-5	20	1.06E+2
7123	320	-9	18	8.15E+1
8140	280	-17	16	3.67E+1
8980	250	-23	15	2.16E+1
10237	210	-31	8	6.13E+0

Table A2. (Cont'd.)

Altitude (m)	Pressure (mm)	Temperature (°C)	Humidity (%)	Mixing ratio (ppm)
Tokyo - August 9 - 1800 hours				
43	754	28	76	1.83E+3
984	680	24	78	1.64E+3
2030	600	20	59	1.09E+3
3087	530	15	49	7.44E+2
4090	470	8	44	4.72E+2
5202	410	-1	36	2.33E+2
6011	370	-6	34	1.68E+2
7138	320	-10	28	1.17E+2
8151	280	-16	26	6.54E+1
8994	250	-21	26	4.56E+1
10251	210	-30	24	2.03E+1
Tokyo - August 9 - 2200 hours				
43	755	25	91	1.83E+3
953	680	22	76	1.41E+3
2024	600	17	67	1.03E+3
3067	530	11	56	6.54E+2
4056	470	5	50	4.36E+2
5156	410	-3	37	2.07E+2
5971	370	-6	31	1.53E+2
7098	320	-12	29	1.04E+2
8107	280	-17	28	6.42E+1
8944	250	-24	28	3.67E+1
10195	210	-32	25	1.72E+1

[a]Read as 1.65×10^3, etc.

Table A3. Winds aloft at Tokyo on 6 and 9 August 1945

Altitude (m)	Wind direction (degrees)	Wind speed ($m\ s^{-1}$)
Tokyo - August 6 - 1000 hours		
0	320[a]	1
200	340	1
500	10	1
1,000	330	2
1,500	20	3
2,000	80	5
3,000	180	3
4,000	230	3
5,000	100	1
6,000	270	3
7,000	270	3
8,000	190	7
9,000	190	5
10,000	180	7
11,000	150	6
12,000	100	1
Tokyo - August 9 - 1400 hours		
0	0	0
200	120	5
500	180	3
1,000	180	7
1,500	330	3
2,000	310	6
3,000	250	6
4,000	240	7
5,000	260	9
6,000	270	11
7,000	260	9
8,000	260	13
9,000	260	13
10,000	260	14
11,000	260	21
12,000	250	15

[a]Direction of wind blowing from north to south is 0 degrees, east to west is 90 degrees, etc.

approximately 1 and 10 km. The values derived from the time-dependent sets of data on temperature vs altitude in Tables A1 and A2 ranged from a low of 5.3 °K km^{-1} to a high of 6.2 °K km^{-1}. Use of a constant temperature lapse rate is thought to be reasonable since ground warming had started in both Hiroshima and Nagasaki prior to the bombings (see Tables 6 and 7).

Estimating humidities as a function of altitude is more difficult. However, summaries of data on mean mixing ratios in Table 3.25 of the Handbook of Geophysics and Space Environments[9] and Table 20 of the U.S. Standard Atmosphere, 1976 (Ref. 10) suggest an exponential model can be assumed for altitudes up to approximately 4 km. A vertical e-folding distance for the mixing ratio of 2.8 km with a standard deviation of about 0.3 km was obtained next by applying the method of least squares to the pooled data on mixing ratios vs altitude between ground level and approximately 4 km. Vertical e-folding distances ranging from a low of 2.0 to a high of 5.0 km were derived from the time-dependent sets of data on mixing ratios between the surface and approximately 4 km in Tables A1 and A2.

The late evening data from Fukuoka on 5 August 1945 and Toyohasi on 6 August 1945 indicate heavy clouds aloft. If these data are eliminated and a vertical e-folding distance is calculated using only the pooled data from Tokyo and 6 and 9 August 1945, then one obtains a value of 2.6 km with a standard deviation of about 0.2 km. The 2.6-km and 2.8 km values give, however, less than a 2% difference in the estimated humidities at the burst heights in the two cities. Hence, the empirical constants derived by pooling all the relevant data in Tables A1 and A2 were used for the atmosphere over Southern Japan ATB.

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APPENDIX B

Chemical composition of dry soil from Hiroshima and Nagasaki

A summary of data on the chemical composition of dry soil from Hiroshima and Nagasaki is given in Table B1. Two soil samples from undisturbed areas in each city were analyzed: one taken as close as possible to the hypocenter, and one taken at a larger ground distance from the hypocenter.[1] The samples were sterilized by heating at the port of entry by the U.S. Department of Agriculture. After arriving at the Oak Ridge National Laboratory, the samples were dried by heating for an additional 24 hours at 105-110 °C, and then ground to less than 100 mesh using a shatter box.[2] Standard chemical methods relying on gravimetric measurements were used to obtain data on a few elements such as H, C, N, and O. However, the primary techniques of obtaining data on nearly 50 elements in the dry-soil samples (see Table B1) were either neutron activation analysis[3] or atomic emission spectrometry using inductively coupled plasma (ICP) systems.[4,5]

About one-half to one gram of a soil sample was nondestructively analyzed by neutron activation analysis.[2] The ICP technique requires a solution for analysis. Two chemical methods were used for dissolution: a HNO_3-HF digestion, and a lithium borate fusion. The HNO_3-HF digestion volatilizes Si, and frequently Cr is not completely dissolved. Of course, the lithium borate fusion method makes both Li and B analysis impossible. Solutions of each soil sample and a certified quality-control sample were run on two differently designed ICP systems. One operated by G. F. Larson in Product Certification at the Y-12 Facility in Oak Ridge, and the other operated by D. R. Heine of the Analytical Chemistry Division at ORNL. The neutron activation analysis was done by J. F. Emery and K. J. Northcutt of ORNL's Analytical Chemistry Division.

Table B1. Chemical composition of dry soil from Hiroshima and Nagasaki

Element	Relative mass (mg/g of soil)[a,b]			
	Hiroshima A-Bomb Dome	Hiroshima Castle	Nagasaki Hypocenter Monument	Nagasaki University
H	5.3[c]	10.1[d]	10.0[e]	10.9[f]
Li	0.028	0.026	0.026	0.026
B	0.0068	0.0040	0.022	0.021
C	10.8	26.3	24.4	27.7
N	0.2	1.6	1.5	1.7
O	501	447	503	490
Na	16.0	12.4	7.89	7.50
Mg	2.54	2.71	8.20	7.35
Al	71.0	64.9	99.6	97.0
Si	334	328	245	244
P	0.168	0.512	1.07	0.959
Cl	0.115			0.340
K	35.9	31.1	7.64	7.54
Ca	8.1	5.4	11.6	11.6
Sc	0.005	0.005	0.002	0.002
Ti	1.57	1.52	5.86	6.32
V	0.0223	0.0253	0.167	0.171
Cr	0.0205	0.0273	0.151	0.152
Mn	0.467	0.587	1.31	1.26
Fe	17.7	20.6	57.3	58.8
Co	0.0037	0.0038	0.0227	0.0222
Ni	0.005	0.009	0.053	0.054
Cu	0.036	0.034	0.057	0.051
Zn	0.113	0.335	0.256	0.230
Ga	0.022	0.022	0.023	0.025
As	0.0044	0.0066	0.0090	0.0081
Se	0.0012	0.0012	0.0020	0.0037
Rb	0.230	0.225	0.070	0.068
Sr	0.088	0.070	0.134	0.124
Y	0.020	0.014	0.020	0.019
Zr	0.041	0.035	0.126	0.127
Nb	0.007	0.005	0.010	0.011
Mo	0.0006	0.0014	0.0020	0.0015
Ag	0.0002	0.0002	0.0014	0.0015
Sb	0.0014	0.0008	0.0060	0.0013
Cs	0.005	0.005	0.004	0.004
Ba	0.521	0.535	0.370	0.341
La	0.023	0.021	0.023	0.023
Ce	0.040	0.036	0.043	0.043

Table B1. (Cont'd.)

Element	Relative mass (mg/g of soil)[a,b]			
	Hiroshima A-Bomb Dome	Hiroshima Castle	Nagasaki Hypocenter Monument	Nagasaki University
Sm	0.0034[c]	0.0030[d]	0.0039[e]	0.0040[f]
Eu	0.0009	0.0009	0.0015	0.0016
Tb	0.0006	0.0006	0.0004	0.0002
Hf	0.0040	0.0040	0.0060	0.0061
Ta	0.0008	0.0008	0.0006	0.0005
Pb	0.086	0.066	0.062	0.060
Th	0.0133	0.0099	0.0070	0.0072
U	0.0028	0.0026	0.0025	0.0039
Total	1006.2	954.3	986.1	974.6

[a]Values given in table are simple averages when data were obtained from both ICP systems or from the ICP systems as well as the neutron activation analysis.

[b]Soil collected between ground surface and a depth of 5 cm (or 2 inches).

[c]West side of Hiroshima A-Bomb Dome.

[d]Near moat at Hiroshima Castle.

[e]About 3 m north of the Nagasaki Hypocenter Monument.

[f]About 430 m east of hypocenter at playground of the Nagasaki University School of Medicine.

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