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Operation CASTLE

Pacific Proving Grounds

Addendum Report for Project 4.1

PHYSICAL FACTORS AND DOSIMETRY IN THE MARSHALL ISLAND RADIATION EXPOSURES

by

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December 1955

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HEADQUARTERS FIELD COMMAND, ARMED FORCES SPECIAL WEAPONS PROJECT
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NOTICE

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ABSTRACT

This report is an addendum to the final report of Project 4.1, Operation CASTLE. Its purpose is to consider the physical factors and dosimetry of the fallout on the Marshall Islands from the first shot of Operation CASTLE.

Data was summarized from field Radiological Safety surveys, fallout radiochemical studies, and fallout gamma spectral measurements. The influence of these and other factors on an evaluation of survey meter response and total dose estimates was considered. Estimates of fallout duration times and energy distribution of the dose from a plane source were made and the effect of diffuse source-geometry on the depth-dose to air-dose relationship was considered. Superficial doses from soft gamma and beta radiation were also considered.

Since the fallout incident created an initial emergency during which data collection was of secondary importance, attempts to reconstruct the event have been uncertain. Much of the data was indicative rather than exact. However, a fairly consistent estimate of external gamma dosage was possible, although the question of beta exposure remains mostly unanswered. It has been assumed that no significant neutron or alpha particle exposure occurred. Internal doses from inhaled or ingested material and the bio-medical aspects of the incident have been discussed in other CASTLE Project 4.1 reports.

It was concluded that: (1) the AN/PDR-39A requires a correction factor of about plus 20 percent in dose-rate readings made under the conditions described; (2) decay of the radioactivity of the fallout is believed expressible by the factor of $T^{-0.83}$; (3) the external gamma dose was delivered primarily by radiation energies of 100, 700, and 1500 kev; (4) the beta dose was delivered by beta radiation of maximum energies of 0.3 and 1.8 Mev, mostly from fallout deposited on the skin itself; (5) the exposures occurred between 4 and 78 hours after the detonation - the fallouts were probably of 12-hours duration; (6) diffuse source geometry increased the midline dose by about 50 percent compared to the midline dose which would have resulted from a bilateral narrow beam exposure of the same air-dose; (7) error in the estimates is believed to be less than 50 percent; and (8) total air gamma doses were estimated as follows: Rongerik, 86 r; Rongelap, 182 r; Ailinginae, 81 r; and Utirik, 13 r.

FOREWORD

This report is one of the reports presenting the results of the 34 projects participating in the Military Effects Program of Operation CASTLE. For readers interested in other pertinent test information, reference is made to WT-934, Report of the Commander, Task Unit 13, Military Effects Program. This summary report includes the following information of possible general interest.

(a) An over-all description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation time, etc., for the operation.

(b) Discussion of all project results.

(c) A summary of each project, including objectives and results.

(d) A complete listing of all reports covering the Military Effects Test Program.

ACKNOWLEDGMENTS

The encouragement and assistance of Dr. E. P. Cronkite, Project Officer of Project 4.1, Operation CASTLE, is gratefully acknowledged. LTJG R. Sharp (MSC) USN aided in the collection of much of the information in the field and assisted with the calculations.

Data relevant to dosage calculation were made available by many sources. Information on energy distribution of the gamma radiation was furnished by Dr. C. S. Cook and the Nuclear Radiation Branch at the U. S. Naval Radiological Defense Laboratory (NRDL). Radiochemical data supporting calculated radioactive decay rates were supplied by Dr. C. F. Miller, Dr. N. E. Ballou, and the Chemical Technology Division of NRDL, and Dr. R. W. Spence of the Los Alamos Scientific Laboratory (LASL).

CDR F. W. Chambers (MSC) USN of the Naval Medical Research Institute (NMRI) kindly furnished field depth dose data obtained at Operation UPSHOT/KNOTHOLE. Particular thanks is due: Colonel C. E. Maupin (MC) USA of Field Command, Armed Forces Special Weapons Project, and Dr. H. Scoville, of Headquarters, Armed Forces Special Weapons Project.

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CHAPTER 1

INTRODUCTION

The fallout on the Marshall Island atolls of Rongelap, Rongerik, Ailinginae, and Utirik from the first shot of the series beginning 1 March 1954 created an initial emergency during which the gathering of data was of secondary importance. This fundamental fact has resulted in uncertainty in all attempts to reconstruct the circumstances of the event. Calculation of the external doses received by the exposed individuals has required that available information be supplemented by assumptions. Much of the information itself was necessarily more indicative than exact. In spite of these difficulties, the cooperation of many individuals and groups made it possible to develop a fairly consistent estimate of external gamma dosage, although the question of beta exposure must remain mostly unanswered.

It has been assumed that no significant neutron or alpha particle exposure occurred. Thus, the main consideration in this report is the total body gamma radiation exposure. Internal doses from inhaled or ingested material have been discussed elsewhere (Reference 1).

Data which form the basis of the analysis were furnished by several sources which are listed in the References. These represent measurements made both in the field and in the laboratory in the period immediately following the exposure. Later information has also been included wherever it was available. A summary of these results appears in Reference 16, which covers the biological and medical aspects of the incident.

CHAPTER 2

FIELD DOSAGE DATA

2.1 EARLY DATA

When the exposures began, no monitoring personnel were in the vicinity of any of the contaminated islands. One of the first indications of a fallout was visual, when a snow-like material was observed in the air on each of the islands. The reports on the times of observation, although conflicting, serve to establish the time of arrival of the cloud at each island, except at Rongerik (see Chapter 6). Here the first evidence of a radiation field was observed when a low-level gamma background monitoring instrument at the weather station began to register and then went off scale at 100 mr/hr at approximately H + 7.4 hours. Table 2.1 lists the readings of this instrument during the half hour preceding this time (Reference 2). These data are the only information available on the initial rate of increase of gamma dose rate on any of the islands.

At the time of evacuation of the military personnel from Rongerik on 2 March and the Marshallese from Rongelap, Ailinginae, and Utirik on 3 March, dose rate readings were made on each island. This was done with AN/PDR-39 radiation survey meters which were available at the time and which had not been calibrated beforehand. Their operating condition was not known at the time of use. The readings of these instruments are given in Table 2.2, and constitute the earliest data on gamma dose rates in any of the areas (Reference 3).

2.2 EXPOSURE CONDITIONS

So far as is known, the individuals exposed on Rongelap and Ailinginae remained outdoors and had no access to shelter of any kind on the islands. No measures were intentionally taken to protect the skin, but clothing was worn to a degree sufficient to shield from most of the deposited beta activity. In addition, much of the fallout skin contamination was removed from some individuals, as a result of their swimming and fishing in the lagoon at the time. On the other hand, the heavy coconut oil hair dressing used by the Marshallese tended to concentrate radioactivity in the hair. The surface contamination on the ground was apparently fairly uniform over the islands, so that the calculation of average gamma doses from this source appears justified.

TABLE 2.1 - Radiation Intensity at Rongerik During Early Fallout (Shot 1)

Time after H hour (hr)	Gamma Dose Rate (mr/hr, background)
6.5 (1345 1 March)	0.08
6.87	0.18
6.91	0.70
6.95	2.7
7.04	3.6
7.12	10.5
7.20	30
7.29	60
7.37	100

TABLE 2.2 - Early Dose Rate Data (2 to 3 March)

Island	Time after H hour (hr)	Average Dose Rate (mr/hr)
Rongelap	H + 36	1500
Rongerik	H + 28.5	2000
Ailinginae	H + 58	445
Utirik	H + 55	160

On Rongerik, the exposed individuals recognized the nature of the fallout, put on protective clothing, and took advantage of the partial gamma shielding afforded by Butler-type buildings in the area, staying indoors as far as possible. The radiation dose rate encountered by an individual on this island thus depended on his whereabouts and probably varied by a factor of two between maximum and minimum values in different areas at a given time. The estimation of dose received by any one individual of the Rongerik group was thus subject to considerable uncertainty, since no complete record of movements was kept.

However, a group of film badge readings was obtained covering a range of values which varied with exposure conditions (Reference 3). These readings are summarized in Table 2.3. Several badges were worn both outdoors and indoors. One badge which remained outdoors over the 28.5-hour exposure reached the upper limit of 98 r given in the table. Several other badges kept inside a refrigerator indoors gave the lowest value of 38 r. Skin contamination in the Rongerik group appeared to have been much reduced by the protective measures taken and the resulting beta doses appeared clinically to have been clearly lower than in the other groups.

TABLE 2.3 - Film Badge Readings on Rongerik

Location of Badges	Calculated Dose to Badges (r)
Indoors and Out	44 to 52
Outdoors only	98
Inside Refrigerator Indoors	38

2.3 LATER SURVEYS

During the period 8 to 11 March, more extended surveys of each of the islands were made by a monitoring team equipped with five AN/PDR-39 instruments (Reference 4). Twenty-four hours previous to the departure of the survey party, three of the instruments were calibrated on an 80-curie Co^{60} source and cross checked at 0.320 r/hr, where they were found to be in close agreement. Using these instruments, measurements were made in the inhabited areas of all four islands at waist height (approximately 3 feet above ground). Table 2.4 is a summary of these data. Since these later readings were made under better controlled conditions than the emergency surveys at the times of evacuation given in Table 2.2, the data of Table 2.4 were taken to be the best measurement at a given time of the gamma dose rates in air and were used in the calculation of the total external gamma dose.

No information existed on the quantity of beta contamination on the skin of any of the exposed individuals. Further, no experimental data allowed any reliable calculation of the beta dose rate to an individual from fission products on the ground. Thus the only basis for any estimate of external beta dosage was data from other field tests and fallout measurements. This question is discussed further in Chapter 8, and a rough estimate for possible beta dose from the ground is made there.

TABLE 2.4 - Later Dose Rate Data (8 to 11 March)

Location	Time after H hour (days)	Avg. Dose Rate (mr/hr)
Rongelap:		
average	H + 7	375
maximum		450
one point in village	H + 7	280
	H + 10	170
Rongerik:		
*average outdoors	H + 9	280
*maximum outdoors		300
Ailinginae:		
average	H + 9	100
Utirik:		
average	H + 8	40

*Dose rate inside structures found to be about ½ that outside.

CHAPTER 3

FALLOUT CHARACTERISTICS

3.1 EXPERIMENTAL DATA

In order to calculate a total gamma dose received by an individual in an area where dose rate was measured at a given time, a value for the rate of change of radiation intensity during the exposure period must be assumed. The latter quantity has often been approximated using the well known Way-Wigner ($t^{-1.2}$) decay law. In this case however, it was known that large amounts of Np^{239} and Np^{240} were to be expected in the fallout of the 1 March shot, making its early decay characteristics as well as its energy spectrum somewhat different from those of previous detonations. It was therefore decided, that the value of decay rate assumed to exist during the exposures should be based, as far as possible, upon experimental data from this test.

Unfortunately, no decay rates were followed closely in any of the immediate areas where the exposures occurred, and it is known that the radiochemical composition and decay rate of the fission product mixture usually vary both with place and time. However, early decay rates in the Bikini lagoon itself had been measured in a series of fallout samples taken at other points nearer the site of the detonation (Reference 5). Since these values were the best data available, they were used in the calculations and were assumed to hold for the fallout on each of the islands.

The early samples showed a consistent pattern among various locations and a decay exponent (n) of between 0.8 and 0.9 in Equation 3.1.

$$A = A_1(t/t_1)^{-n} \qquad (3.1)$$

where: A = activity (d/m) at time t.

This decay exponent (n) was found experimentally to fit the data for the period H + 5 to H + 50 hours. The observed values are given in Reference 5.

CHAPTER 4

GAMMA ENERGY-DOSE SPECTRUM

4.1 PHOTON FLUX SPECTRUM

The fallout material deposited on the ground produced a large area plane source of radiation. Before a total gamma dose could be calculated, it was necessary to correct the dose rate readings in air taken with the survey instruments with the meter response factors found to be necessary for different energy regions. Further, to estimate the distribution of dose with depth in tissue required a knowledge of energy distribution of the incoming flux in a given exposure geometry.

For a source as large as these fallout fields, this energy distribution will be a function both of the original source energy and the energy degradation effect of passage through intervening air. A method of evaluating the latter, which was due mainly to Compton scattering in air for the fission product energy region, has been presented in Reference 7. This technique was employed here. Energy spectra of the CASTLE fallout itself has been measured with a scintillation spectrometer on a series of cloud samples as early as H + 4 days. The data have been published in Reference 8. The preliminary data on the earliest of these, a 94-hour-old cloud sample, were used in the calculations summarized in Reference 16. These are given in Table 4.1 (Reference 9). This 94-hour sample from Shot 1 represents the closest approach to the actual time during which the exposures occurred.

CHAPTER 6

DURATION AND TIME DISTRIBUTION OF DOSES

6.1 AVAILABLE DATA

In Chapter 2, the only existing field data on dose rates and total dose are summarized. The information does not provide answers to two important questions: (1) what was the time for each island at which the fallout cloud arrived; i.e., when did the radiation level on each of the islands rise above the normal background and (2) how steeply and for how long did the radiation-level rise before it reached its maximum value and decayed away at the rate determined by its own composition (discussed in Chapter 3); i.e., how heavy was the fallout at any time it was occurring and how long did it last? Since only the times of evacuation were directly known, assumptions on both these questions were basic to an estimate of total dose.

It would have been desirable to have had an instrument on at least one of the islands capable of recording enough data to answer these questions. As it is, it was fortunate that there was even a low-level monitoring instrument in operation on Rongerik (Table 2.1), although its full scale capacity was soon exceeded by the rapidly increasing dose rate of the fallout. The time at which the fallout began was at least quite definitely established on Rongerik and it coincided with the time at which the snow-like material was first seen.

For the other islands, therefore, the times at which similar material had been seen to commence falling could be taken as the beginning of the radiation exposure times. It only remained to determine what these times had been.

Questioning the inhabitants of the other islands resulted in a group of estimates of arrival time which were in fairly good agreement, though the manner of questioning sometimes appeared to influence the answers. However the times estimated in this fashion were quite close to those resulting from other information; i.e., the wind velocities at the time, the time of beginning fallout on Rongerik, and the relative distances of the other islands from Bikini. Only on Utirik was no actual observation of the fallout made; the estimate of arrival time there was made using only the time of arrival on Rongerik and the wind-and-distance-factors. The values of fallout and evacuation times used are summarized in Table 6.1.

TABLE 6.1 - Fallout and Evacuation Times

Island	Estimated Initial Fallout Times (hours)	Evacuation Time (hours)
Rongerik	H + 6.8	H + 28.5 (8 men) H + 34 (20 men)
Rongelap	H + 4	H + 50 (16 people) H + 51 (48 people)
Ailinginae	H + 4	H + 58
Utirik	H + 22	H + 55 to H + 78

6.2 ESTIMATES OF FALLOUT DURATION

The rate of increase of radiation intensity, the time at which it reached its maximum level due to decrease of fallout, and the total duration of the fallout can only be estimated on circumstantial grounds. The data of Table 2.1 for Rongerik are not sufficient to warrant an extrapolation over two orders of magnitude. It is unlikely that the increase of intensity was simply linear either on Rongerik or any of the other islands. But, if the rate of increase is assumed constant and extrapolated to a point for which subsequent decay alone would reduce the dose rate to the values found at later times, a fallout time of 16 hours on Rongerik, for example, is found to be a necessary consequence (Curve a, Figure 6.1). That is to say, 16 hours would have elapsed at such a constant fallout dose rate increase before the time of maximum dose rate on the island would have occurred - the time at which the fallout was increasing the radioactivity level at the same rate that radioactive decay was reducing it. For such a constant build up, this equality would have occurred only for an instant, (Point A_1), after which the fallout would have suddenly ceased.

The actual fallout must, of course, have had a variable rate of increase and decrease, reaching a maximum and gradually decreasing to the rate governed by decay alone. However, using the initial rate of increase and drawing a more gradual maximum would place the cessation of the fallout at an even later time (Curve b, Point A_2). Since the visible fallout is believed to have ceased sometime after midnight on 1 March or at about H + 18 hours (Point A_3), an increase in the rate of increase after a short time was almost certainly the case (Curves c, d, and e). But the steepness of this rate of increase, the sharpness of the maximum point and the gradualness of the fallout diminution are unknown, so that there is no direct evidence to show whether Curve c or Curve e, for instance, is closer to representing the event.

There are, however, indirect indications. Monitor data from previous nuclear events have indicated that a radioactive cloud is not uniformly high in activity throughout, the first portion being the most intense and the balance tailing off. Initially heavy fallout has been reported to produce a peak of airborne radioactivity soon after its arrival, with the airborne activity level then decreasing. The latter part of a fallout, though still observable as dust, may then add only a small fraction to the total dose due both to aerosol and material already on the ground, especially if radioactivity was mainly confined to the larger particles which fell out most quickly. If this is the case, the total phenomenon would tend toward the effect of a shorter fallout, and the total dose would then be best estimated by assuming the fallout to have been complete in some shorter "effective" time, such as Curve f.

The Rongerik film badge data in Table 2.3 may be used to derive such an effective fallout time estimate. This procedure was followed. The decay rate, energy spectrum, and meter response discussed in Chapters 3 and 5 were used and the later dose rate measurement on Rongerik (Table 2.4) was taken as a starting point. The upper limit of dose found with the outdoor badge readings (approximately 100 r Table 8.1) then resulted from assuming a 12-hour "effective constant fallout" time. This was, therefore, taken as a most probable time and the resulting straight line midway between Curves a and f in Figure 6.1 was used in calculating the probable 12-hour dose for each island (Curve g). Though this estimate differs appreciably from that of 1 hour which was originally used as an effective time in Reference 16, the later spectrum, decay rate, and meter response estimates made a 12-hour value more plausible if the film badge readings were accepted.

Keeping a 1-hour assumption would have resulted in a dose some 50 percent higher than the outdoor badge readings showed. Since the accuracy of the film badge readings was believed to be better than 50 percent, the 12-hour value was therefore used, as it is more consistent with all the other available information. Nevertheless, the duration of fallout still remains the least known parameter of the exposures.

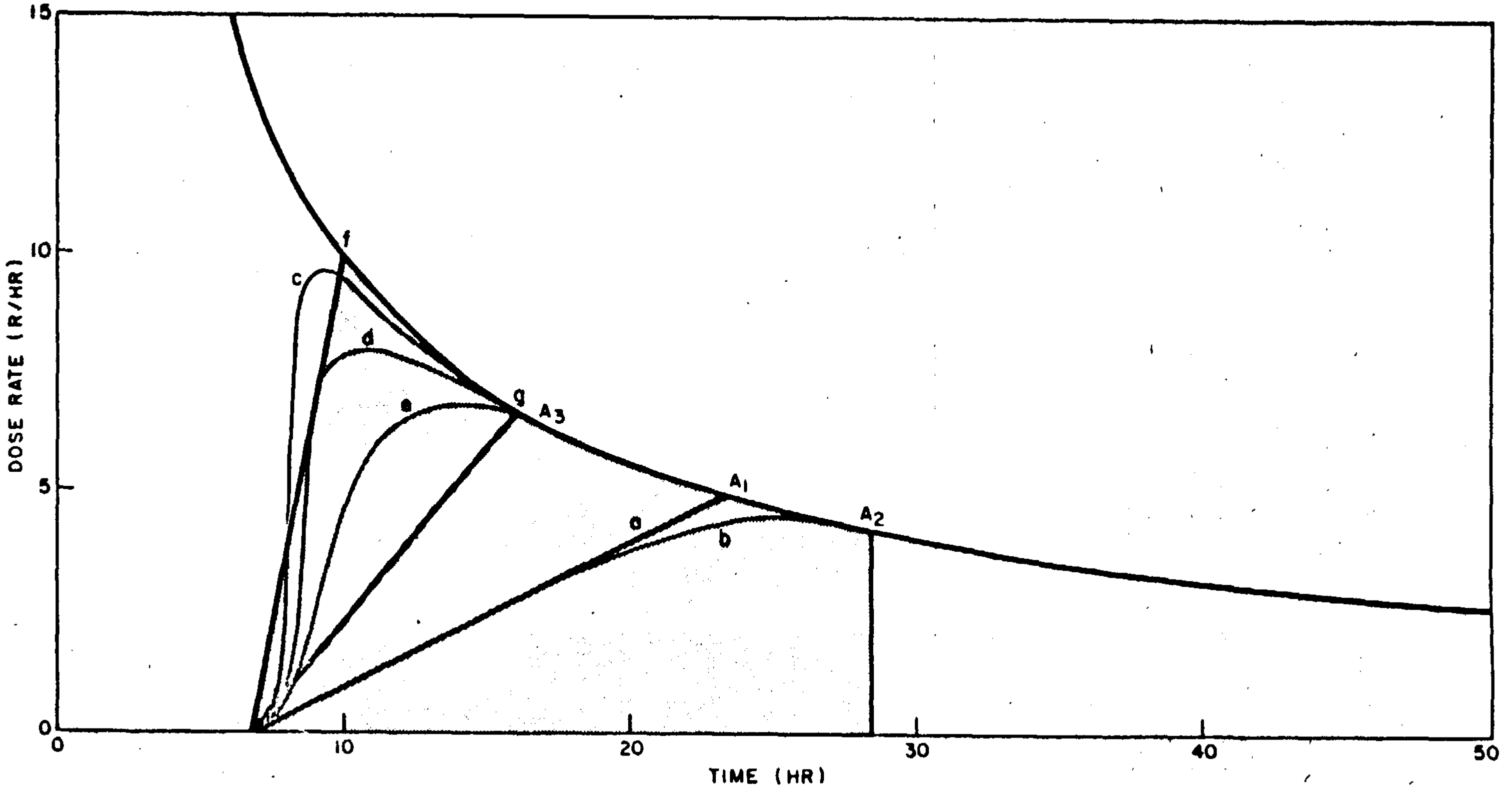

Fig. 6.1 Fallout Dose Rate Versus Time Estimates, Rongerik Atoll

~~SECRET — RESTRICTED DATA~~

CHAPTER 7

EXPOSURE GEOMETRY EFFECTS

7.1 DISCUSSION

In clinical and laboratory exposures, the radiation flux usually follows a narrow beam or at least a point-source "divergent" geometry. When an air-dose is used to specify the exposure conditions for a thick target, it is generally measured at the point subsequently occupied by the center of the proximal surface of the patient or experimental animal with respect to the source. For field exposures such as occurred on the islands, the radiation source is not a point and the exposure geometry is "diffuse" rather than "divergent."

When a cloud or a large planar area is the source, all surfaces of the irradiated individual are "proximal," in the sense that the air-dose measured anywhere in the space subsequently occupied by the individual is the same. It is this air-dose which is measured by a field instrument; it does not bear the same relationship to the skin dose and depth dose as does the air-dose measured in a point source geometry. If a bilateral exposure is made in the laboratory, one-half the dose is usually given with one side of the individual facing the source and one-half with the other. This is a closer approach to the field geometry. But, if the air-dose has been measured at the center of the proximal surface as above, it is still not related to the depth dose in the same way as is the field air-dose.

The doses received by the individuals on the islands were from both the cloud itself and the fallout deposited on the ground. It is believed likely, as discussed in Chapter 6, that the cloud dose was only a small part of the total dose and that the dose from the plane ground source contributed the major portion. This corresponds to the assumption of early maximum activity and short effective fallout time which was made in Chapter 6 for the maximum dose case. Alternatively, if a long fallout actually occurred, the source would have remained a cloud longer and the cloud volume, rather than the surface distribution, would have accounted for more of the total dose. In either case, it would appear that the midline dose, rather than the dose measured in air, would be the better common parameter in terms of which to predict biological effect. Since most existing data tacitly assumes narrow beam geometry, this distinction becomes important in relating field air-doses and their consequences to known clinical or experimental results (References 11, 12).

~~SECRET - RESTRICTED DATA~~

7.2 EXPERIMENTAL SIMULATION AND GEOMETRY FACTOR

In such a diffuse field, the decrease of dose with depth in tissue is less pronounced than that resulting from a bilateral exposure to an X-ray beam and the relationship to air-dose differs as noted in the two cases. The result is that, for a given energy, the dose at the center of the abdomen is considerably higher than a given proximal air-dose would imply for the narrow-beam or point-source case.

Figure 7.1 illustrates the depth dose curve in a 36-cm diameter cylindrical masonite phantom from an experimental simulation of the field geometry (Reference 13) using a spherically oriented group of 36 Co^{60} sources. The phantom was placed at the center of the assembly. This is compared to a conventional bilateral depth-dose curve measured in the same phantom and obtained with a single Co^{60} source. Both are normalized to air-dose, but the average air-dose at all points later occupied by the phantom surface is implicit for the diffuse case, while the proximal air-dose is used in the bilateral case.

Figure 7.2 is a similar comparison for 200-KVP, 0.5-mm, copper-filtered X-rays, with the diffuse geometry that of a plane rather than spherical source assembly. This was produced in this case by rotation of the phantom and ion chamber in the beam of a stationary X-ray unit. The useful beam angle of the unit was wide enough to include the whole phantom. The average air-dose around the circumference was here used for the diffuse geometry and the proximal air-dose again in the bilateral exposure. It is evident that for both these energies (the effective energy of the X-ray beam being about 90 KV), the diffuse-narrow beam depth dose ratio for either 2π radians (plane) or 4π steradians (volume) diffuse geometry is almost the same. That is, the midline dose is about 50 percent higher and the 5-cm dose is 35 percent higher than the same air-dose (measured proximally) would imply in the narrow beam bilateral exposure. It is therefore assumed that this approximate factor will apply throughout the field exposures.

On this basis the air-dose values calculated from the survey meter readings (Table 8.1) should be multiplied by 1.5 in order to compare the situation to that of a bilateral exposure to a source with the same energy distribution but using a point source geometry and a proximally measured air-dose. Alternatively, if a point source of higher energy, say Co^{60}, were used bilaterally in the same way to simulate a field exposure to only the higher gamma components, then the meter energy correction factor would be unity. In this case, to specify a bilateral exposure yielding a midline dose equal to that with diffuse geometry, the point source air-dose should be the diffuse field air-dose measured with the meter and multiplied by (1.09 x 1.5) only.

The doses are discussed further in Chapter 8.

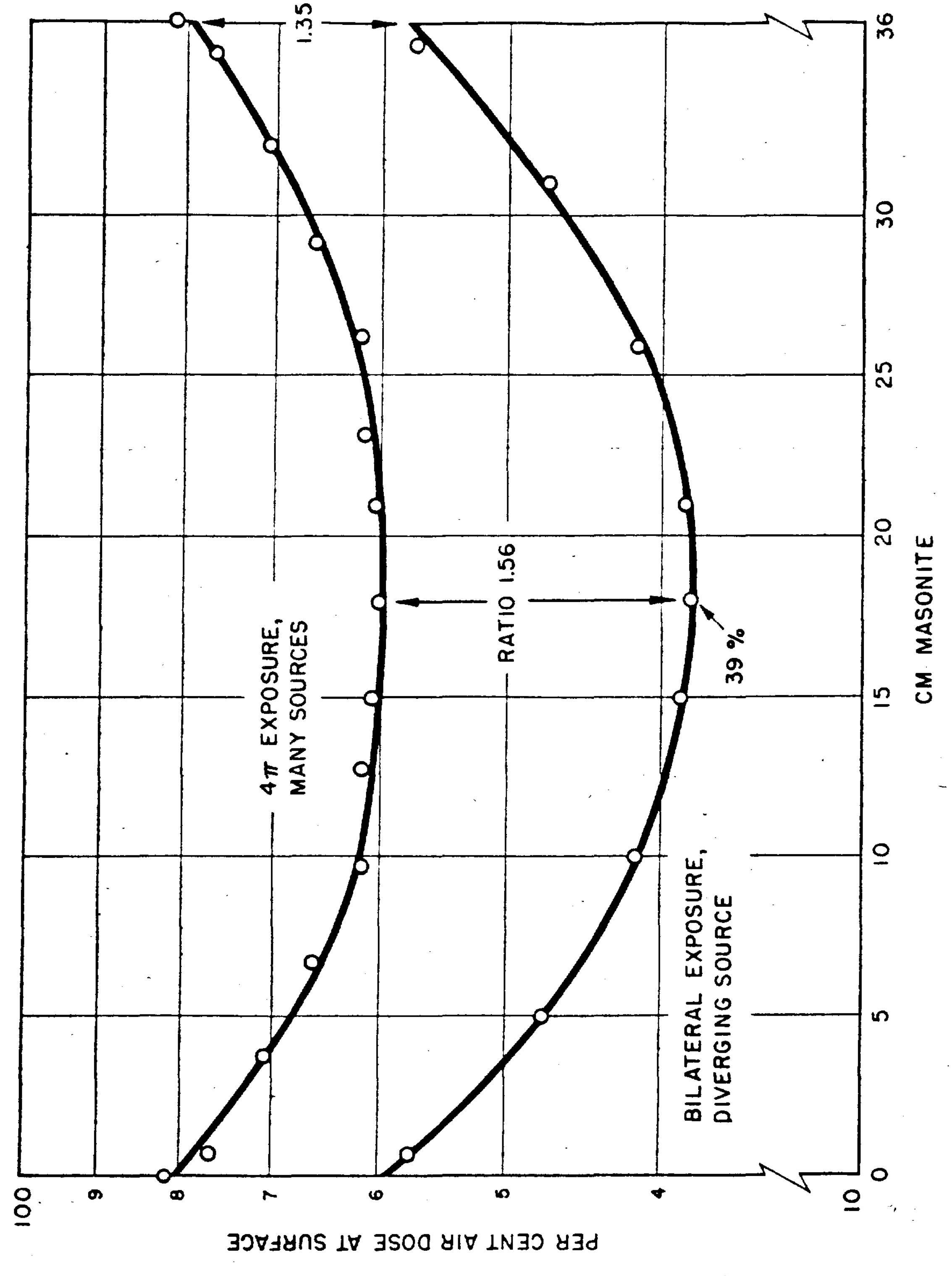

Fig. 7.1 Depth-Dose Curves, 36-cm Phantom, 1.2 Mev

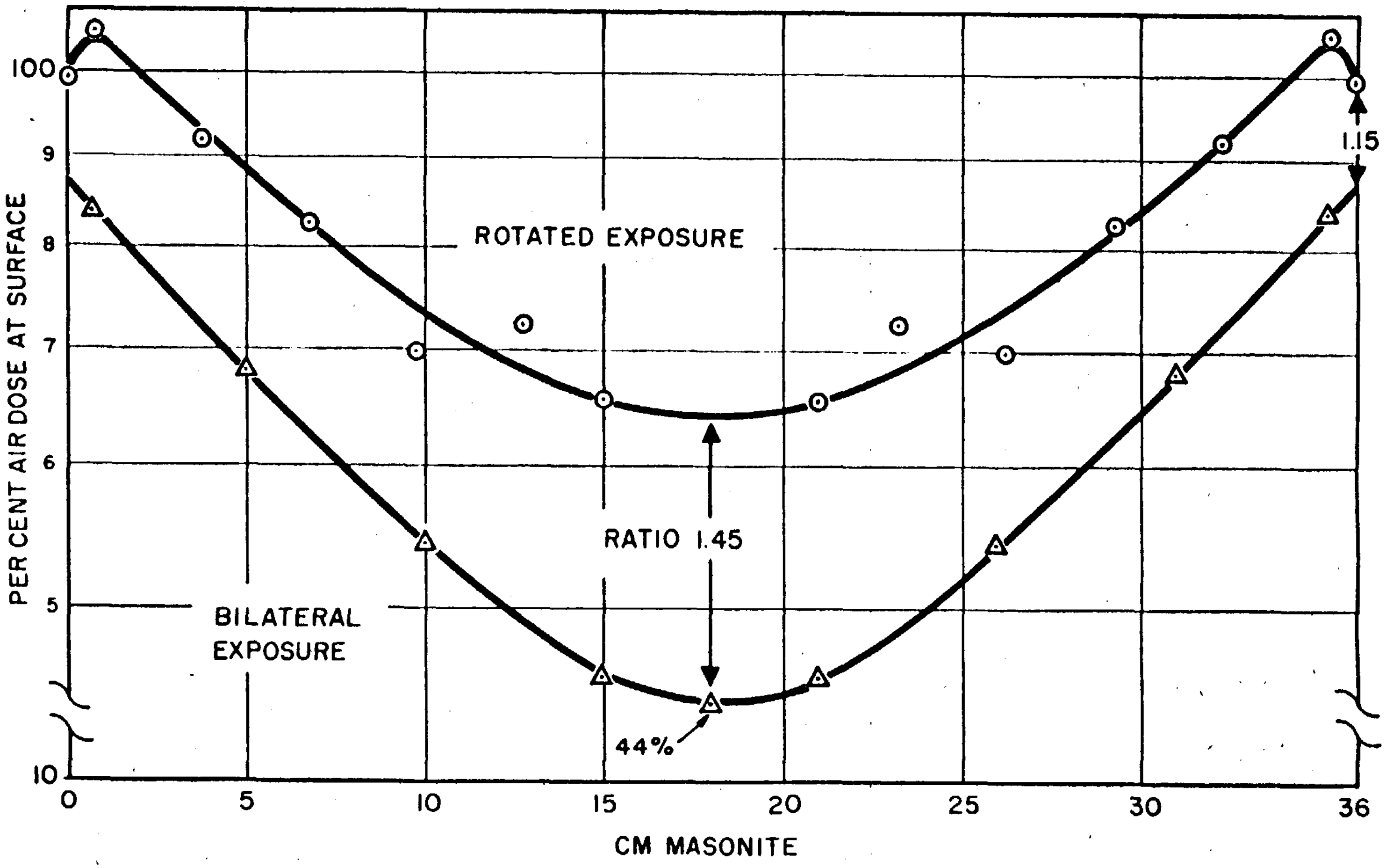

Fig. 7.2 Depth-Dose Curves, 36-cm Phantom, 200 KVP