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BIOLOGICAL EFFECTIVENESS OF NUCLEAR RADIATIONS FROM FISSION WEAPONS

by

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ABSTRACT

Thermal neutron measurements made on five weapons during Operation Teapot indicated that these neutrons contribute at most 2 per cent of the total neutron dose in air. However, the total fluxes were high and thermal neutrons may become important under certain shielding conditions and may significantly affect the response of the film badges and certain sensitive dose detectors, especially when the neutron to gamma flux ratio is high.

The fast neutron measurements indicated the varying importance of fast neutron dose depending on weapon type. The measurements also showed spectral invariance in rather wide energy bands over one to six mean free paths from point of detonation. The variation of flux seen by any single detector (e.g., sulfur) was found to be a variant of weapon design.

Chemical dosimetric systems showed that gamma dose inside lead shields used for animal studies was due to neutron-gamma interaction in lead and constituted less than 10 per cent of the total radiation dose inside the shields. Also, gamma dose measurements in air using the chemical systems compared well with film badge measurements made in air (at distances where the neutron to gamma dose ratio was 1 or less) at this and previous tests.

The biological results showed that the RBE of fission neutrons between 100 and 1000 rem was 1.7 when spleen-thymus weight loss in mice was used as the endpoint. Secondly, it was shown that additivity of neutrons and gamma rays varied with the neutron to gamma ratio. Finally, at very high doses and very high dose rates the RBE of neutrons appeared to decrease when median survival time was used as the biological endpoint.

Using previous test results and the Teapot findings, it was possible to determine neutron and gamma dose versus distance curves for other fission weapons, in particular for those of the Japanese detonations. On the basis of these curves, the human effects observed in Japan were correlated with physical dose, and estimates of various parameters of effect in humans were made. These included (1) the RBE of fission neutrons for acute death in humans, 1.6 ± 1.6; (2) the LD_{50}^{30} for humans, ~700 rem; (3) the SD_{50} (acute) in humans, ~275 rem; (4) the distribution curve for 30-day death in a human population. A discussion of the errors in the above estimates is included.

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CONTENTS

TABLES

ILLUSTRATIONS

1. Introduction

Investigations of the biological effectiveness of nuclear radiations from fission weapons have been pursued at several weapon tests, including Operations Greenhouse, Tumbler-Snapper, and Upshot-Knothole. These investigations primarily concerned acute responses of mammals (in particular, mice) to neutron and neutron plus gamma radiations from various types of atomic devices. The radiation doses were delivered at the time of burst and studies did not include the effects of remaining residual contamination. Two sets of data on humans, namely, the results of the Hiroshima and Nagasaki detonations, are available for comparison.

Certain gaps existed in these data which made it impossible to evaluate completely the biological effects of nuclear radiations on humans. The findings among the Japanese casualties have been well-documented.[1-4] However, the physical doses of radiation are not known absolutely and past correlation of dose with test results has been uncertain or impossible. A variety of biological and physical dose measurements are available from the various weapon tests. The physical doses of gamma rays have been reasonably well determined; physical doses of neutrons are unknown. Much of the biological data is of little value for direct comparison purposes, either because the device used as a radiation source was one unrelated to any weapon of the present or future, or because the biological test system used was not suited for field measurements, the only reason for the test being to use an atomic device as a "convenient" source of radiation.

In the summer of 1954, representatives of the Health Physics Division of the Oak Ridge National Laboratory and of the Biomedical Research Group of the Health Division of the Los Alamos Scientific Laboratory discussed measurements which should be made during Operation Teapot in order to answer many of the questions regarding nuclear radiation effect as related to neutron and neutron plus gamma dose. From these informal discussions a project developed which involved joint participation of the above groups with the addition of Lt. Sanford Sigoloff on loan from the School of Aviation Medicine, Randolph Air Force Base, Texas. The project was included in the Civil Effects Test Group programs directed by R. L. Corsbie for administrative and logistic support. These programs were ably supported by the Division of Biology and Medicine of the U. S. Atomic Energy Commission, the Federal Civil Defense Administration, and the Los Alamos Scientific Laboratory.

2. Objectives and Methods

The project was designed to make certain physical and biological measures of dose versus distance from detonations of atomic devices.

Each set of measurements was designed to answer certain questions arising from previously obtained data or to add new data important for prediction and correlation purposes. The exposure methods used were essentially the same as those used in past field experiments and utilized the same materials.

A primary consideration in project planning was neutron dose measurement. Up until the time of Upshot-Knothole, no absolute measurement of neutron dose in terms of rep had been made. At that time a few measurements were made to field test a system of measurement developed by Hurst and co-workers at the Oak Ridge National Laboratory. The same system was utilized for this project. The method was essentially a foil activation procedure in which the degree of activation of the foils can be related to neutron dose.

Several types of foils were used. The difference in activation of gold foils and gold foils covered with cadmium was a measure of the total thermal neutron flux which is easily related to thermal neutron dose through theory and laboratory experimentation.[5,6] Also, this method had been used in flux measurements made at most previous tests which afforded a basis of correlating the Teapot tests with past detonations.

The activation of sulfur is a second method of flux determination, which has been used frequently in past tests. The sulfur value yields the total number of neutrons in the energy range greater than the 2.5 Mev threshold. The proportion of total neutron dose contributed by neutrons of these energies can be readily calculated from single collision theory. These two methods, however, give no information on neutrons of energies between thermal and 2.5 Mev. This gap in the spectrum may be completely covered by using an appropriate fission foil system.[7] Above certain energies, the fission cross-sections for Pu^{239}, Np^{237}, and U^{238} are flat, so that measurements of fission activation from neutrons above their respective threshold energies can be used to determine the total number of neutrons within certain energy regions.

By surrounding the foils with B^{10}, it is possible to eliminate interfering capture and fission reactions. The difference in fission activation between any pair of foils is an accurate measure of the total neutrons in the energy interval between their respective fission thresholds. These values may then be related to neutron dose by application of the single collision curve for neutron dose in tissue and the error in measurement will be small, as long as the dose per neutron does not vary rapidly with energy throughout the selected energy range. Also, the method allows a complete coverage of the neutron spectrum, as the lowest activation threshold is near the cadmium-cutoff value of the gold foil system. The method is effectively energy-independent, rate-independent and gamma-insensitive. The method is accurate for any dose greater than 10 rep.

During Operation Teapot fission foil, sulfur, and gold measurements were made in air and in hemispherical lead containers on five detonations. The lead hemispheres had 7-inch walls and were the same ones that had been used at previous tests for animal exposures to neutrons only (Fig. 1).

The neutron dose measurements were made for several reasons. First, such measurements were important because of an apparent dependence of neutron yield per kiloton on bomb design. Such variations were first found in biological and flux measurements for different detonations at Operation Greenhouse. Flux and biological measurements at subsequent tests have confirmed such variations. By making absolute measurements of neutron dose it would perhaps be possible to derive the functional variation of dose with the design of any particular fission weapon and relate measurements made on bombs of this series to incomplete measurements made on other series. Second, neutron doses may become of extreme importance in the use of high neutron yield weapons both for exposures in air and in shielded geometries, as shielding criteria are certainly different for neutrons and gamma rays. Third, in the extrapolation of test results to human information, neutron dose variation with weapon type is important. The radiation casualties from Hiroshima and Nagasaki were caused by bombs radically different in type, that could be expected to give radically different neutron yields. Fourth, neutron dose data both inside the lead animal containers and in air were needed. Flux measurements on previous tests indicated that the lead perturbed the total neutron population and thus decreased by an unknown amount the dose to the animals inside.

Physical measurement of gamma ray dose was an important aspect of the entire project. Gamma ray dose measurements, using film packets, have been made at all test series to date. Generally, the correlation of measured gamma dose from one experiment to another has been good. However, the badge system appeared to give anomalous results, especially in the lead hemisphere containers in experiments where the neutron yield was high. Therefore, a gamma dose measuring system of another type was selected as a corollary to the film measurements. The system selected was a chemical dosimeter method first developed by Sigoloff and others at the University of California at Los Angeles and further refined by Sigoloff at the Radiobiology Laboratory of the School of Aviation Medicine.[8] The chemical dosimeter consisted of a dehydrated chloroform solution which, after exposure, was colorimetrically and titrametrically measured after addition of an appropriate dye. The chloroform solution was in sealed siliconized Neutraglas ampules which were placed in Lucite containers, wrapped in 0.5 mm lead and varying thicknesses of lithium metal. Laboratory studies of these dosimeters have shown that they are energy-independent above 100 kev, rate-independent up to at least several thousand rep per minute, and their dose response is linear above 50 rep. The fast neutron response of these dosimeters is negligible, whereas the thermal neutron response is considerably decreased by wrapping with lithium metal.

A second system was also used. This system consisted of trichlorethylene saturated with water and is sensitive to both neutrons and gamma rays. By a comparison of the results of both systems, it is possible to determine gamma plus neutron rep, gamma rep only and, by subtraction, neutron rep only. Film badges were also used. These were packets of several films in a polyethylene, tin, and lead shield having the same characteristics as similar badges developed at the National Bureau of Standards.[9] These badges were furnished, developed, and read by Edgerton, Germeshausen and Grier under AEC contract. Chemical dosimeters of both types were placed in the hemispherical lead shields and in the 1/4-inch aluminum shields used for gamma plus neutron measurements (Fig. 2). Film badge measurements were made in air and inside the shields.

The various gamma ray measurements were made for several reasons. Generally, the gamma ray dose per kiloton of yield has been consistent from one fission type weapon to another. Some variation has been detected, but this may be primarily due to variance in the data. In any case, the measurements should be made at any experiment in order to account for unrecognized shielding problems introduced by tower-cab materials or actual variation in gamma yield. Second, a true measure of the gamma dose inside the lead hemispheres is very important. All calculations indicated that this component of dose was low. However, in some experiments conducted previously, anomalous high results were found (using film badges as dose detectors).[10] These results may have been due to neutron effect and a check was necessary using the neutron insensitive chemical dosimeter. Third, measures of gamma dose had to be made in the aluminum exposure device for correlation with animal response. The ratio of gamma to neutron dose is not constant but varies with distance, since the mean free paths of neutrons and gamma rays (even though inversely proportional to air density) are quite different. The measurements of both gamma ray and neutron dose as a function of distance are essential for the prediction of total dose in any given situation.

Three biological measurements of radiation effect were included in the project. These measurements were made using CF_1 female mice. The methods were chosen for simplicity, adaptability to field conditions, and because of previous field use. One measurement involved organ weight loss as an index of radiation effect. Weight loss of the spleen and/or thymus has been used both in the laboratory[11-14] and in all previous mammalian radiation exposures at field tests. The method is accurate over the range of 100 to 1,000 rem. Adequate descriptions of the methods are given in the above references. A second biological measure of effect was based on the total body weight loss at 72 hours post-exposure.

This measure appeared to be exponentially related to radiation dose over the range of about 1,000 to 10,000 rem. In this dose region, other measures of effect (such as median survival time) are of no use because the effect is essentially independent of dose. Again, the actual rem dose may be determined by comparison with calibration curves developed in the laboratory. This method had not been used previously in field work. The third method employed to measure biological effect was the median survival time which is exponentially related to dose[15] above 10,000 rem. By early recovery of the animals post-detonation, it was possible to extend the total dose range covered to as high as 100,000 rem. For all three biological test systems, actual dose in rem was determined by comparison of field results with suitable calibration curves established in the laboratory on comparably stressed animals.

The animal exposures were made in both the hemispherical aluminum containers and in the lead exposure units. By comparison of the animal response in lead with the measured neutron dose in rep, the relative biological effectiveness (RBE) of fission weapon neutrons may be measured. This measurement had never been made previously in field experimentation. Measurement of biological dose in the aluminum containers gave the effectiveness of the gamma plus neutron dose, and in conjunction with the data collected in the lead hemispheres permitted the calculation of the effectiveness of fission weapon gamma rays and the additivity of the two radiations. Comparisons could then be made with previous field results, laboratory experimentation on animals, accidental human exposures, the Japanese bombings, etc., to arrive at more reasonable human effectiveness figures.

3. Results

The neutron flux and rep measurements made with the foil system were very satisfactory. The thermal neutron measurements with the gold foils indicated that, at most, only 2 per cent of the total neutron dose in air is contributed by thermal neutrons. However, the total number of thermal neutrons was large and under certain shielding conditions could contribute materially to total dose. For instance, there was no difference in thermal flux in air and in 7 inches of lead, although the gamma dose was decreased enough to be negligible.

Several important findings were made with the fast neutron foil detectors. One of the most important findings is shown in Fig. 3, in which neutron flux times distance squared in relative units is plotted against distance. These data show that the slopes of the curves are the same for all foils. This indicates that the neutron spectrum does not vary over the range of measurement (from one to six mean free paths) and thus under similar conditions, a single foil measurement can be indicative of the total neutron dose.

In Table 1 is collected information showing the portions of the neutron spectrum contributing to the flux and the dose for several different devices. It will be noted that the flux of neutrons greater than 2.5 Mev (which are of most interest since these are determined by sulfur detectors commonly used at all tests) is a known variant of design. By using these results and the spectral invariance characteristic noted previously, it is possible to determine rep dose for other weapons for which the flux data are fragmentary.

For comparison with previous biological experiments, it was found that the 7-inch lead hemispherical shields decreased the rep dose by a factor of 2 in all cases. Finally, it was found that the mean free path for neutron dose is a function of air density and is only negligibly dependent on radical variation of bomb design.

Several results of the chemical dosimeter measurements of gamma and neutron dose are worth noting. A typical graph of these data is shown in Fig. 4, in which dose times distance squared, in relative units, is plotted against distance.

It will be noted that the mean free path of gamma rays measured inside the lead shields is exactly the same as the neutron mean free path in lead or in air. This indicates that the gamma dose measured inside lead was not due to leakage of bomb gamma rays through the lead, but was due primarily to gamma rays originating from neutron interaction in the lead or materials inside the hemisphere. Also, the gamma dose inside the lead is less than 10 per cent of the neutron dose inside the lead. An investigation of the chemical dosimeter neutron results also shows a ratio of 0.5 for the inside lead to inside aluminum results and is consistent with the fission foil measurements. However, the total neutron rep dose as shown by the chemical dosimeters is 20 to 25 per cent less than that shown by the fission foils. This result is consistent with a 30 per cent discrepancy found in laboratory calibration of the two systems. Apparently, the discrepancy arises through a loss of sensitivity of the chemical system for certain neutrons which are detected by the fission foils. The gamma dose curve found inside the aluminum exposure units is typical and compares well with film badge measurements made at previous tests, both as to dose per kiloton yield and as to mean free path as determined at the Nevada Test Site.

The film badge measurements made on these experiments indicated the following. First, the badge measurements made inside lead were unsatisfactory over most of the range. It is apparent that neutron response of the film badge used precluded reasonable results in any situation in which the neutron flux or dose yield was high compared to the gamma dose. This effect is also indicated by in-air or aluminum measurements where the neutron dose was much greater than the gamma dose. The effects are due to at least three mechanisms: (1) fast neutron response; (2) immediate thermal neutron response; and (3) thermal neutron activation with delayed response. Thermal neutron effects cause a high proportion of the total response because even though the neutron dose contribution is low, the total numbers of thermal neutrons present are high. The film badges gave two items of information which are important. There was no significant difference between film badge dose measures in aluminum and in air. This result indicates that, at least for the energy range seen by the film badge, the 1/4-inch aluminum shield does not absorb a significant proportion of the gamma photons. Secondly, it was found that there is no significant difference in gamma ray dose at levels of 1 to 3 feet above the surface of the ground, but the dose decreases rapidly below the surface as ground shielding becomes important and only air scattered radiation is accepted.

The biological results determined by splenic and thymic weight loss at 5 days post-irradiation were as consistent as expected. Biological dose in rem times distance squared, in relative units, versus distance is shown in Fig. 5. By comparison with Fig. 4 it will be noted that even in the aluminum-shielded stations the mean free path for the response is more comparable to the neutron mean free path than to that for gamma rays, which indicates that neutrons produced a very significant portion of the total measured response.

One of the most important measurements made with the spleen-thymus weight loss system was an accurate evaluation of the RBE of the neutron radiation from fission weapons. No accurate evaluation of effectiveness had ever been made previously because in no case was the physical dose known. From physical measurements made at this series of tests an accurate measurement of total neutron rep was determined for all stations. Also, the gamma dose has been evaluated and has been shown to be less than 7-1/2 per cent of the total, so it may be neglected. The measured biological dose in rem determined by spleen-thymus weight loss is plotted against neutron dose in rep in Fig. 6 for all points in all detonations studied. The RBE is thus easily evaluated, being the slope of the resulting curve. The method gave an

RBE of 1.7, which compares very well with results of experiments using a fission neutron source at the Los Alamos Scientific Laboratory. By using this value and determining the rep dose found from biological data at previous detonations, a further check on the rep number calculated from the sulfur data using assumptions outlined previously is possible.

By a comparison of the rem doses determined in the aluminum hemispheres with those in the lead hemispheres, it was possible to check the additivity of fission weapon nuclear radiations. The biological response inside the aluminum was produced by a varying mixture of neutrons and gamma rays, depending on the detonation and on the distance or total dose level, so it was possible to study additivity at varying physical dose ratios. Early biological studies at Operation Greenhouse using the spleen-thymus system indicated that the RBE for bomb gamma rays was 0.8. These experiments have shown an RBE for bomb neutrons of 1.7. Thus, by multiplying the measured rep doses of each component by its respective RBE and summing, a theoretical rem dose could be determined.

The ratio of the measured rem dose to the theoretical rem dose for each aluminum station was then developed. In Fig. 7 this ratio has been plotted against the neutron rep to gamma rep ratio for each station. It is apparent that additivity is incomplete and varies as the proportions of the two radiations in the mixture vary. The additivity (as would be expected) approaches 1 as the gamma ray fraction of dose becomes much less than the neutron fraction. No field experiments are available for the converse situation, where the gamma dose becomes a large portion of the total, but it could be predicted that the curve would show a minimum as the neutron to gamma ratio decreases below the plotted value and then again approaches 1. The determination of incomplete additivity as the neutron to gamma ratio changes is supported by laboratory experimentation.

The median survival time data gave several interesting results. In laboratory calibration, using X- and gamma ray sources, the median survival time plateaus at ~3.5 days over the range of 1200 to 10,000 r and decreases exponentially above this level to 150,000 r (the highest total dose measured).[15] The animals exposed in the field showed exactly the same symptoms with even more uniformity than the laboratory groups. However, if the neutron rem to rep ratio for median survival time as determined in the field from the laboratory calibrations is plotted against the total neutron dose in rep as shown in Fig. 8, the RBE appears to decrease with increasing total dose. The main difference between the laboratory and field methods is an extreme difference in dose rate. The highest dose rate used in the laboratory was 9000 r/min, whereas in the field the rate approached as high as 10^7 neutron rep/sec. In laboratory measurements made by Rajewsky[16] to as high as 150,000 r/min, a second plateau in the median survival time curve appeared at a level of 80,000 to 100,000 r. If these data are used for comparison with field neutron results, the effectiveness increases somewhat at the higher neutron doses, but does not come up to 1.7.

It appears, therefore, that effectiveness does vary inversely with dose rate if three conditions are satisfied, i.e., the total dose is high, the dose rate is high, and the specific ionization caused by the bombarding particle is high. It is also implied that if all three conditions are not satisfied simultaneously, but some unknown value for the product of the three factors is high enough, the same result occurs. An inspection of the data of the plateau region of the response also shows the same type of result. As the total rep delivered through the plateau area approaches the 10,000 rep level, the median survival time indicates a decreasing RBE.

The median survival time results inside the aluminum hemispheres support the conclusions made previously. In these cases there was an added gamma dose to the neutron dose. The gamma dose rate was much less than that for neutrons (the total time of delivery being ~90 sec) and the ratio of gamma to neutron dose was low in all cases. Therefore, the additivity should approach 1 and there should be no decrease in gamma effectiveness from high dose rate, etc. By subtracting gamma rem from total rem, the residual neutron RBE may be calculated. These points have been added to Fig. 8, and although the scatter of all data is wide, the agreement between results obtained in the lead and aluminum hemispheres is evident. Again, in the case of the animals exposed in the aluminum stations, the objective findings were exactly the same as seen in the laboratory and the degree of illness was extreme compared to the rem as determined by median survival time measured in the field.

4. Discussion

Although the physical and biological results obtained during Operation Teapot are complete insofar as the devices involved are concerned, two conditions must be satisfied in the application of the results to other weapons, and finally to man. First, the basic assumptions upon which physical dose is estimated in other cases must be valid, and secondly, the further extrapolation and application to man must be based upon sound data rather than theories.

For the determination of physical gamma ray dose in other cases, the necessary bases have been established previously. It can be generally stated that gamma dose scales with kilotonnage and is not a widely variant function of bomb design, at least for fission weapons in the yield range up to ~ 50 kt. It can also be stated that the mean free path in air is a function of air density and is, therefore, inversely proportional to the altitude of the target and directly proportional to the air temperature. If the proportionality constant (which can be deduced from these and other tests) is known, the gamma dose versus distance for any particular set of circumstances can be estimated rather accurately.

The estimation of neutron dose is more difficult due to the variation of flux with design. However, certain of the findings of the present experiments and relations developed from data on other tests are applicable to the problem. First, the spectral invariance demonstrated over a wide range is extremely important. Therefore in the extension of the data to other designs, the proportion of dose or flux measured by any one fast neutron detector is constant over the distance range of interest. However, the question arises of the proportion of dose measured by a single detector being constant from one weapon to another.

In the case of the Teapot field experiments, as far as neutrons measured by sulfur were concerned, the data could be grouped into two parts. The weapon design was quite variant from one group to the other. Moreover, it still cannot be factually concluded that, as variants within each group occur, the proportion of dose contributed by sulfur-measured neutrons is constant. Some estimates of the variation of this proportion of the total dose may be determined by comparison of previous test information in which sulfur flux, biological dose, kilotonnage, and design are known. By using the measured value for RBE of 1.7, the fact that the total rem (or rep) dose is depressed by a factor of 2 by the lead shield, and using results over a range in which effectiveness does not vary, the per cent of total dose contributed by sulfur-measured neutrons can be determined as a function of certain parameters of bomb design. Enough data are available to indicate that this is a slowly variant function of certain design criteria. From these data, it can also be concluded that thermal neutrons are an unimportant part of the total neutron dose and, thus, may be neglected except under certain shielding conditions.

Mean free path variation again is a function of air density and therefore can be calculated similarly to that for gamma rays. Utilizing these data from various tests, it is possible to calculate dose versus distance curves for Hiroshima and Nagasaki. Fortuitously, the two bombs differed radically in design and gave widely variant neutron components of total dose. The parameters necessary for physical dose determination in the Japanese cases and the values used are shown in Table 2. These parameters were determined by evaluation of test data using similar devices and evaluation of data from British, Japanese, and United States investigating teams working in Japan.[17-20] The absolute difference in height of burst is well fixed at 100 yards. The yield at Hiroshima shows a large error but this is dependent in part on the error in Nagasaki yield, as it was determined by comparison. The mean free paths given are the same as those found at Eniwetok. This mean free path is reasonable since the target cities were essentially at sea level and the air temperature was comparable to early morning temperature at Eniwetok, quoted as 28°C in Nagasaki[21] and "hot and humid" at Hiroshima.[22] The zero intercept values shown were determined from a number of similar type devices detonated both in the Pacific and in Nevada.[10,12,23-29] Physical dose in rep using these parameters versus distance are shown in Figs. 9 and 10, using as the basic equation,

$$\text{rep} = \frac{R_o W e^{-D/\lambda}}{D^2}$$

where R_o is the extrapolated intercept constant with units of rep x yds^2/kt, W - yield in kt, D - slant distance in yards, and λ - mean free path in yards.

Casualty data from both detonations may be compared to the physical doses developed above, and comparisons may then be made which give reasonable values for the 30-day LD_{50} dose for humans, the RBE of fission neutrons for acute response in humans, and the distribution of a human population in its acute response to nuclear radiations from fission weapons.

The LD_{50} distances were determined from information given in the Joint Commission reports. It is reported that at Nagasaki an LD_{50} distance for radiation death only was at 1000 meters from Ground Zero.[3] This result was determined from the evaluation of persons exposed at the location of the Fuchi School and finally was based on 26 casualties. At Hiroshima, it was found that at 1000 meters the incidence of radiation lethality was 58.5 per cent which, subtracted from the total mortality curve, leaves a residue of 11.5 per cent which would have been the cause of death from all other causes if combined injury had not covered up radiation effect.[3]

Using these observations and applying the information to both detonations gives the slant ranges with an estimate of the error shown in Table 2.

The basic dose equation may then be solved for the LD_{50} dose using the values appropriate to each detonation. An estimate of the total error may be made by differentiation of the basic dose equation and evaluation of the various constants as shown in the following calculation. The total error in R is made up of

$$(1) \quad \Delta R_{R_o} = \frac{We^{-D/\lambda}}{D^2} \Delta R_o = K_1 \Delta R_o$$

$$(2) \quad \Delta R_W = \frac{R_o e^{-D/\lambda}}{D^2} \Delta W = K_2 \Delta W$$

$$(3) \quad \Delta R_\lambda = \frac{R_o We^{-D/\lambda}}{D\lambda^2} \Delta\lambda = K_3 \Delta\lambda$$

$$(4) \quad \Delta R_D = \frac{R_o We^{-D/\lambda}}{D^2 \lambda} + \frac{2R_o We^{-D/\lambda}}{D^3} \Delta D = K_4 \Delta D$$

and

$$\Delta R_T = \pm(K_1{}^2 \Delta R_o{}^2 + K_2{}^2 \Delta W^2 + K_3{}^2 \Delta\lambda^2 + K_4{}^2 \Delta D^2)^{1/2}$$

The final values are shown in Table 3. It will be noted that the mean LD_{50} values are much higher than would be expected from the popular estimates, even with the associated large error. As would be expected, variation in slant range contributes in high proportion to the total error . A re-evaluation of this parameter from the data collected could decrease the total error by more than 25 per cent.

Combining the dose equations for the detonations using 50 per cent death as the equality endpoint allows the determination of an effectiveness value, E, for fission weapon neutron irradiation as follows:

For Nagasaki

$$\text{(1)}\quad \text{rem} = R_{\gamma}^{N} + ER_{n}^{N}$$

For Hiroshima

$$\text{(2)}\quad \text{rem} = R_{\gamma}^{H} + ER_{n}^{H}$$

$$R_{\gamma}^{N} + ER_{n}^{N} = R_{\gamma}^{H} + ER_{n}^{H}$$

$$\text{(3)}\quad E = \frac{R_{\gamma}^{N} - R_{\gamma}^{H}}{R_{n}^{H} - R_{n}^{N}}$$

where R_{γ}^{N} = gamma dose in rep at Nagasaki; R_{n}^{N} = neutron dose in rep at Nagasaki; R_{γ}^{H} = gamma dose in rep at Hiroshima; R_{n}^{H} = neutron dose in rep at Hiroshima; and E = RBE of fission weapon neutrons. The RBE of fission weapon neutrons determined by this method is 1.6 ± 1.6. It will be noted that the error is large but certainly limits the effectiveness of neutrons on humans when using death as the endpoint response. In these cases, the RBE for fission weapon gamma radiation has been arbitrarily assigned a value of 1, as would be expected from comparison with hard X-ray or radium gamma ray effects on humans. Using these effectiveness values, total dose (rem) versus distance curves may be determined for both Hiroshima and Nagasaki (Fig. 11).

An important corollary to any attempts at target analysis, prediction of effects, or after-the-fact estimates of needed disaster services is an accurate evaluation of the distributional dose response of a usual human population to nuclear radiations. For attempts at evaluation, death versus dose is necessary. However, even more important is casualty versus dose. Casualty must be defined using reasonable symptomological parameters and further delineated according to time of appearance if nuclear radiations are the exciting mechanisms. As a first attempt at determination of the normal distribution curve for humans, the data reported from Japan[3,4] may be used.

In reviewing these data, several facts are immediately evident. First, the higher percentage of radiation symptoms in the Hiroshima survivors at distances inside 1500 meters can be explained. By a comparison with the total dose versus distance curves, it is apparent that the actual Hiroshima dose was higher over this region due to the added neutron component, and over regions where the doses were the same, the percentage incidence of effect was very comparable for the two detonations. Second, the data as reported are not completely satisfactory as the dose changes very rapidly throughout each collection region. Third, the location of affected personnel should be known almost exactly because of the large contribution to the total dose error by variation in slant range noted previously. Both of the last two points tend to broaden the population distribution for humans.

An attempt at the determination of human response to nuclear radiations is shown in Fig. 12. Per cent sickness is plotted against dose and the superimposed curve is the distribution for the population involved. Sickness in this case has been defined as any combination of symptoms referable to the radiation syndrome and includes two late-appearing findings, epilation and purpura, as well as the acute symptoms of nausea, diarrhea, vomiting, anorexia, etc. The points noted have been determined from the Japanese data, the Los Alamos accidents,[30] and the Pacific exposures.[31] An attempt has been made to narrow the response versus dose distribution by considering that the Japanese data were collected from a sampling of survivors living more than 20 days following the bombings, and that the ring analysis used to collate these data gives an extremely wide dose range. Thus, at distances of less than 1000 meters, one can assume that the majority of survivors were near to 1000 meters or were in shielded areas which effectively lowered the total dose down to or below the 1000-meter level. Also, since unrecorded and dead individuals have not been counted, which from the point of view of this report biases the available data, the percentage sickness is greater than that noted. Similarly, at great distances, because of unreported absence of illness, the percentages may be lower than given. The arrows from each point indicate the directions in which the two variables would tend to vary and do not indicate magnitudes. It can be seen, however, that the 50 per cent sickness dose lies between 250 and 300 rem, which is not far different from various other estimates.

Figure 13 shows similar relations for mortality versus total dose. Even though the LD_{50} value is more firmly established than the SD_{50} dose developed previously, there is little available information at other partial levels of effect. It is reasonable, however, to assume that the small sample of individuals from areas inside 1000 meters must include survivors of doses of 1000 rem or greater. Similarly, doses in the region of the SD_{50} where some deaths are recorded are available. Also, at the zero death level are the Pacific exposures and Los Alamos accidents.

In summary, it may be stated that, on the basis of field experimentation and the application of the results, it is now possible within the limits of the errors involved to predict acute casualty, including death, for any particular fission weapon type and to determine from post-fact information the disaster services needed for adequate control of nuclear radiation effects.

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TABLE 1

VARIATION IN CONTRIBUTION OF VARIOUS SPECTRAL REGIONS TO NEUTRON FLUX AND NEUTRON DOSE FOR DIFFERENT TYPE FISSION WEAPONS

	Weapon Type and Spectral Contribution	
	Type 1	Type 2
Spectral Portion	% Total Dose	% Total Dose
4.0 kev to 0.75 Mev	26	26
0.75 Mev to 2.5 Mev	70	66
>2.5 Mev	4	8
	% Total Flux	% Total Flux
4.0 kev to 0.75 Mev	50	50
0.75 Mev to 2.5 Mev	47.5	45
>2.5 Mev	2.5	5

TABLE 2

PARAMETERS USED FOR LD_{50} DOSE CALCULATIONS FROM JAPANESE DETONATIONS

Parameter	Nagasaki	Hiroshima
λ (Mean free path for gamma in yards)	360 ± 10	360 ± 10
λ (Mean free path for neutrons in yards)	220 ± 10	220 ± 10
R_oW (Dose at zero distance for gamma in rep/yd^2)	$4.14 \pm 0.50 \times 10^{10}$	$3.33 \pm 0.93 \times 10^{10}$
R_o^nW (Dose at zero distance for neutrons in rep/yd^2)	$2.07 \pm 0.25 \times 10^{10}$	$1.41 \pm 0.40 \times 10^{11}$
D (LD_{50} distance in yards)	1300 ± 50	1350 ± 50

TABLE 3

HUMAN LD$_{50}$ DOSES FOR MORTALITY WITHIN 30 DAYS DERIVED FROM THE JAPANESE DATA

Radiation Type	Nagasaki	Hiroshima
Rep gamma	660 ± 160	430 ± 170
Rep neutrons	30 ± 10	170 ± 90

Fig. 1 Hemispherical lead exposure assembly used for neutron exposure of animals

Fig. 2 Hemispherical aluminum exposure assembly used for neutron plus gamma exposures of animals

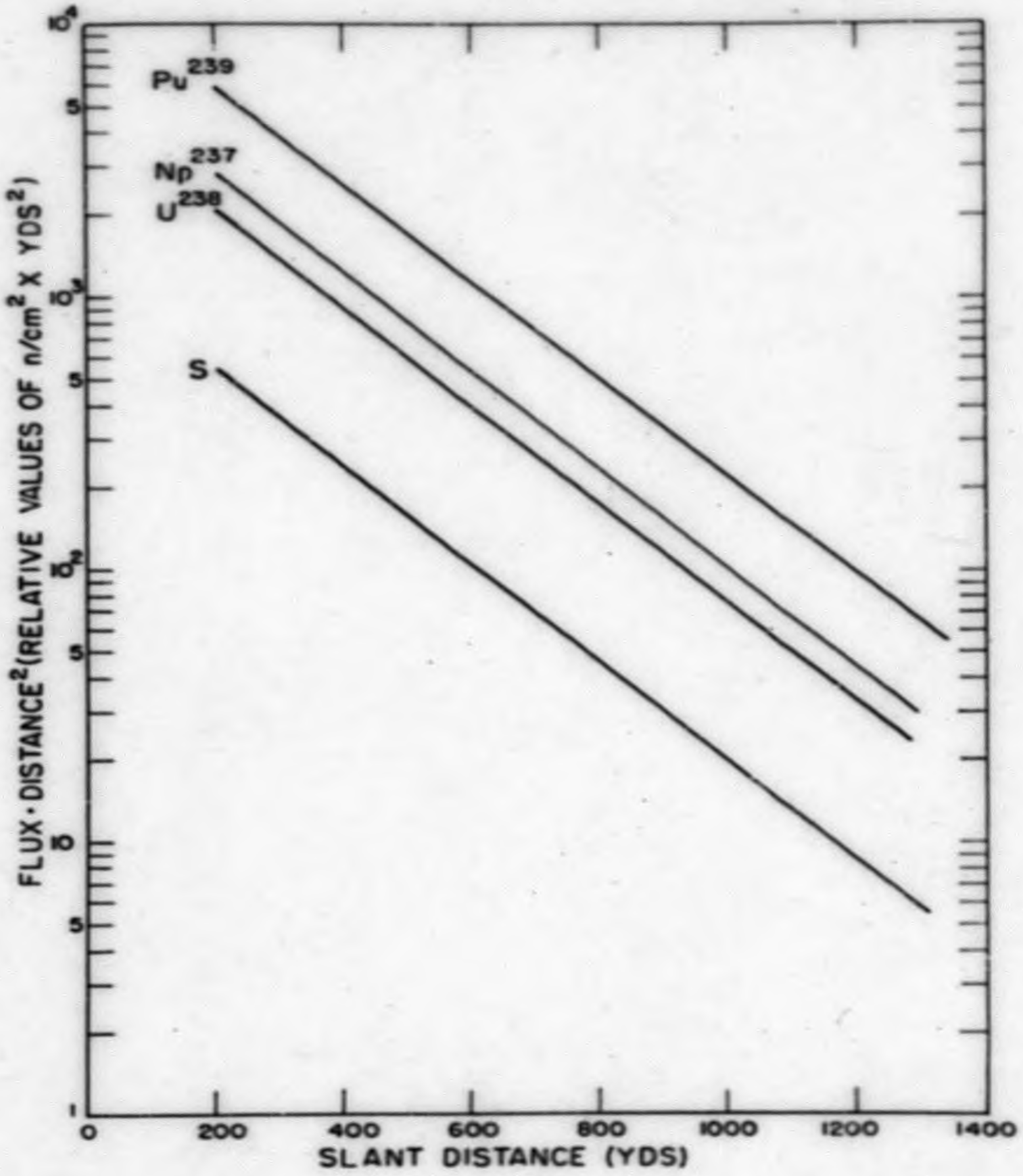

Fig. 3 Flux curves indicating spectral invariance of neutrons with distance from point of detonation

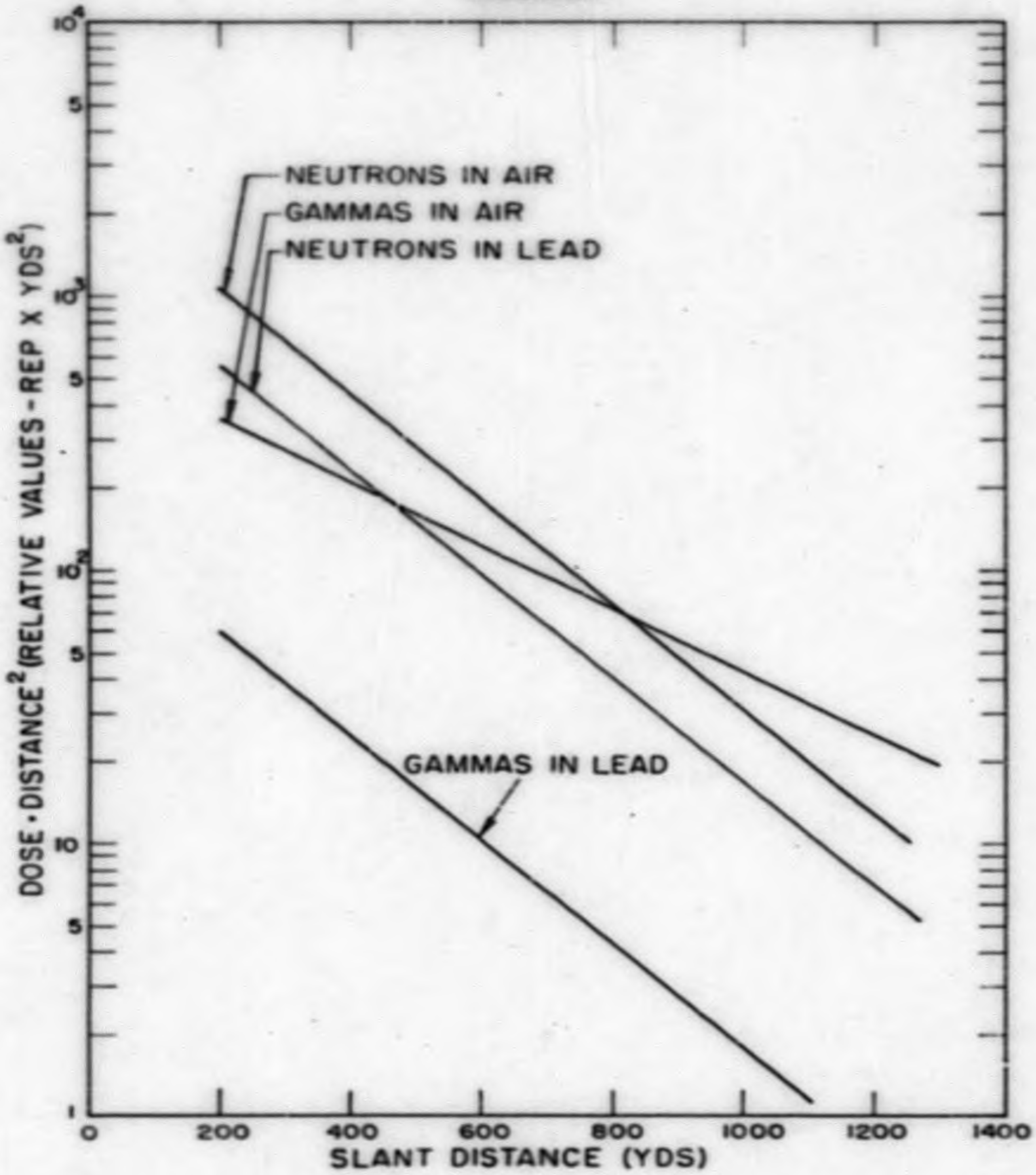

Fig. 4 Results of radiation measurements using chemical dosimeters

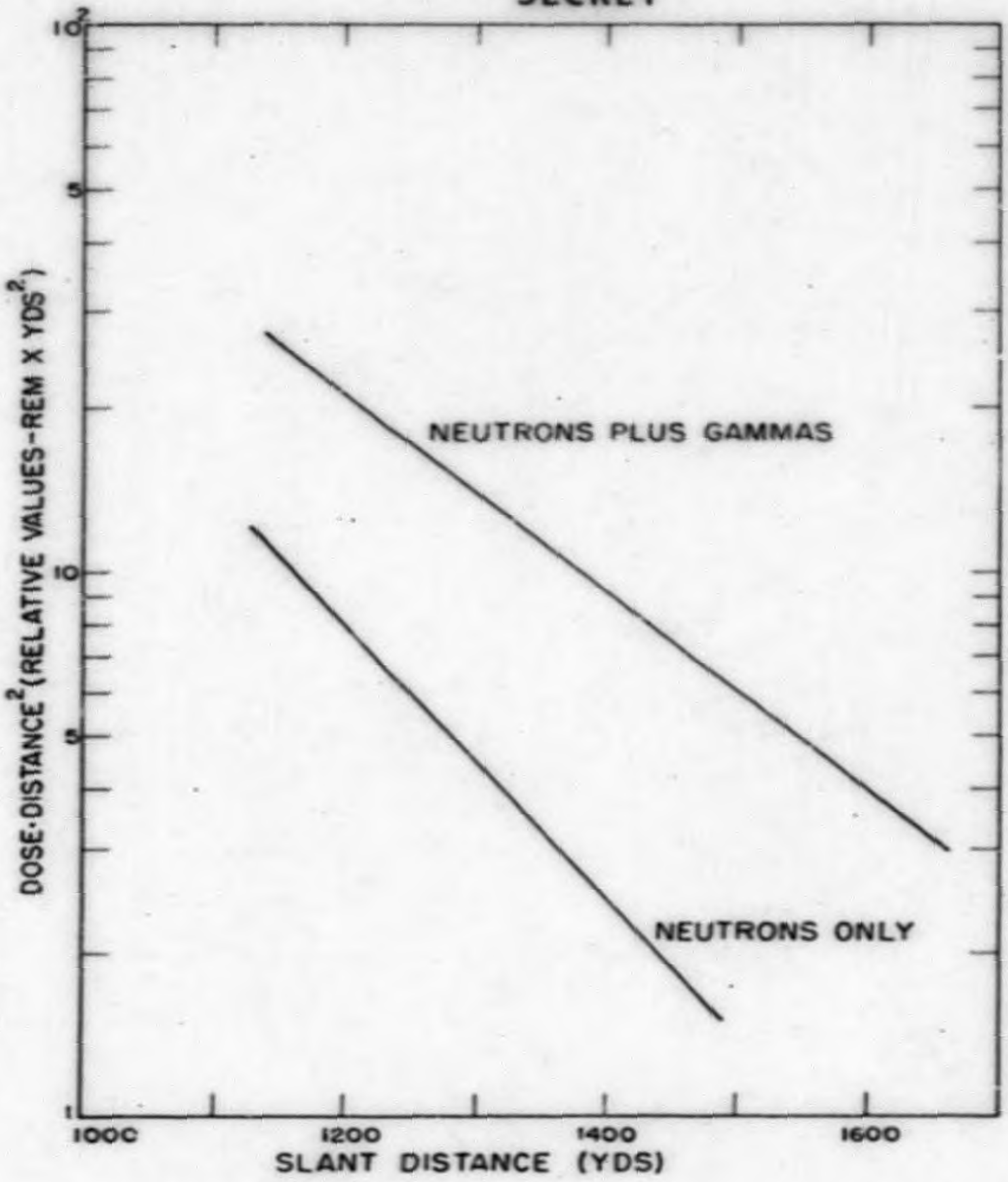

Fig. 5 Radiation dose in rem determined by spleen and thymus weight loss

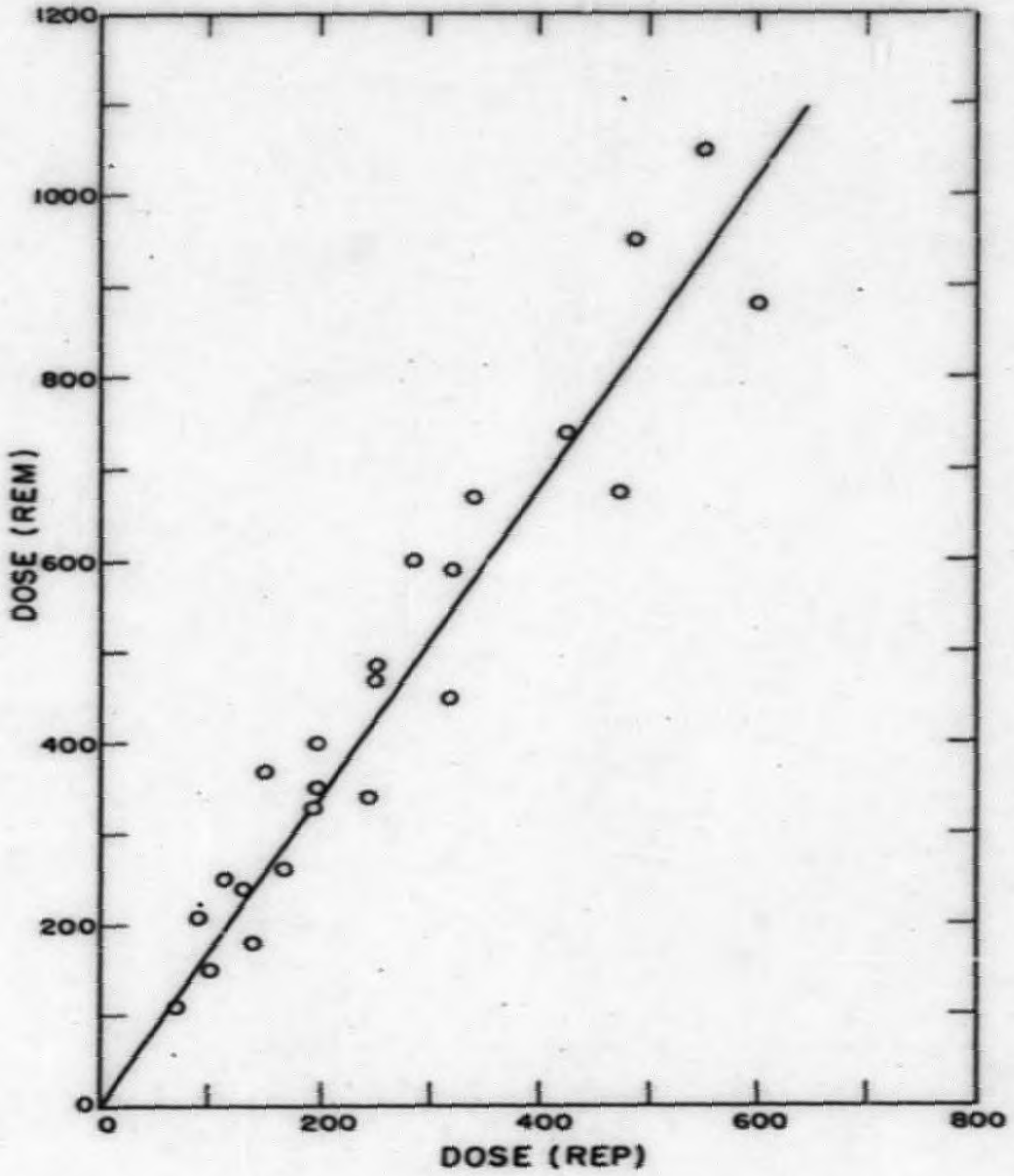

Fig. 6 Relative biological effectiveness of fission neutrons

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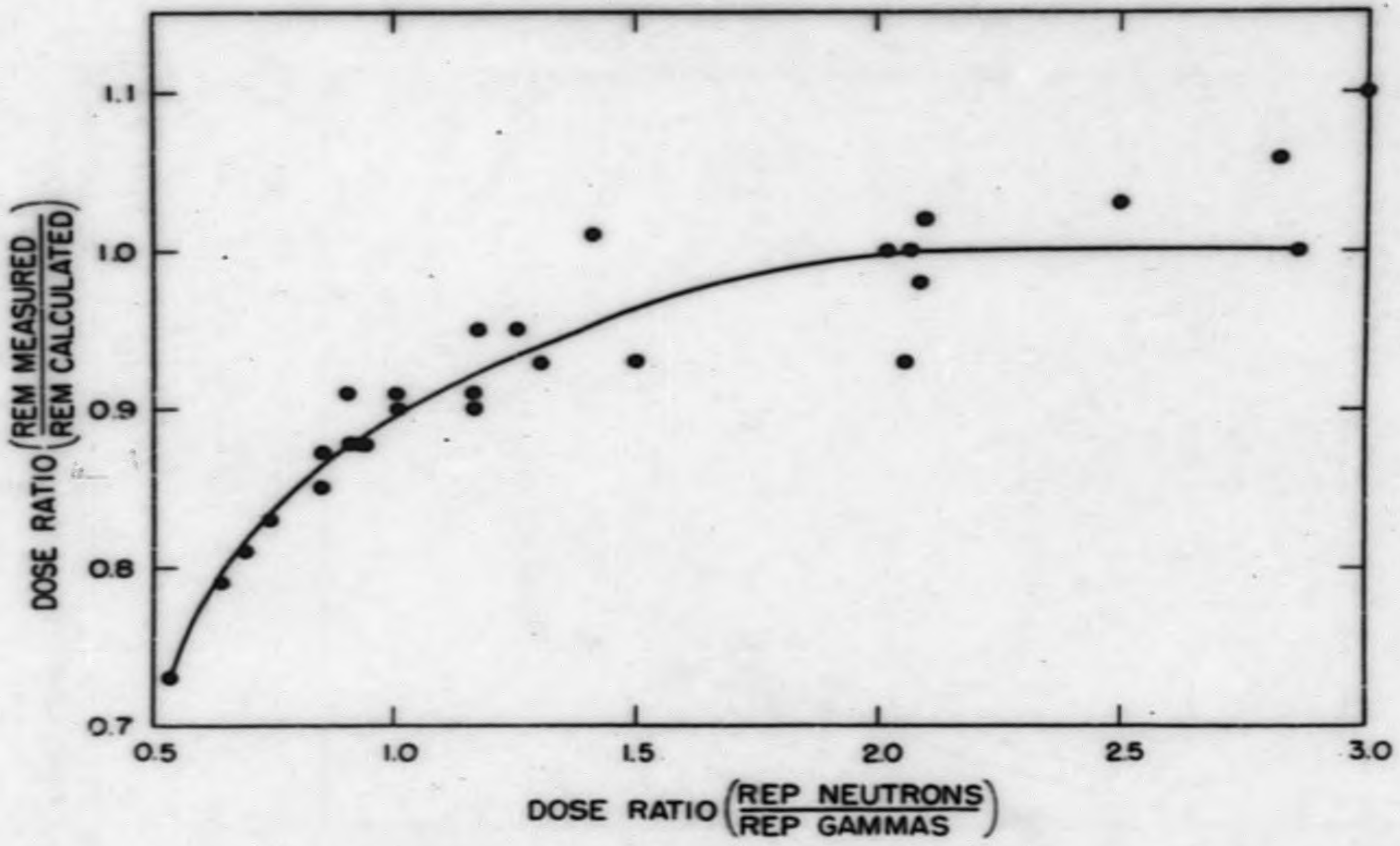

Fig. 7 Additivity of bomb neutron and gamma radiation effect

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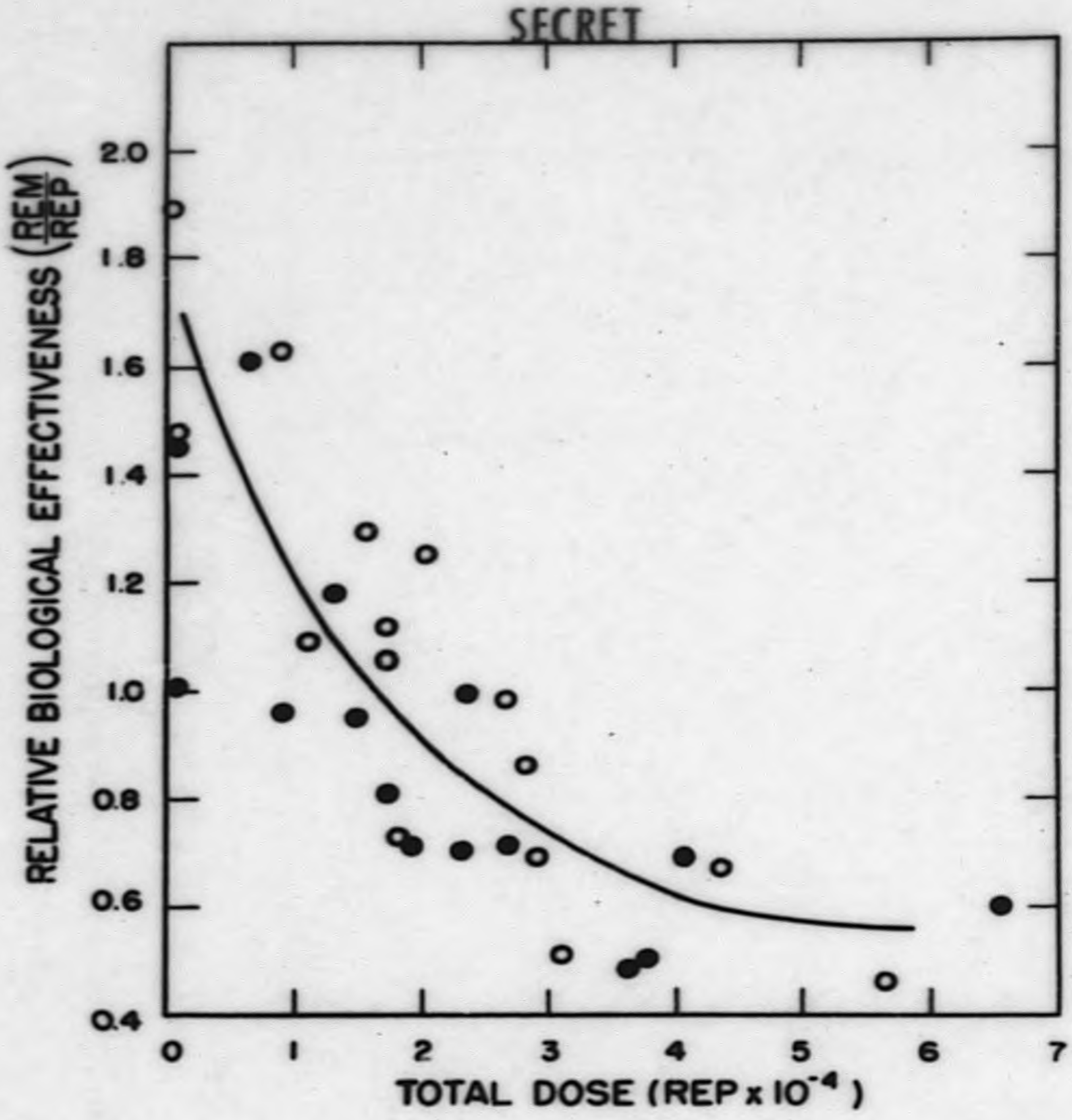

Fig. 8 Variation in neutron RBE with increasing dose using median survival time as the biological indicator

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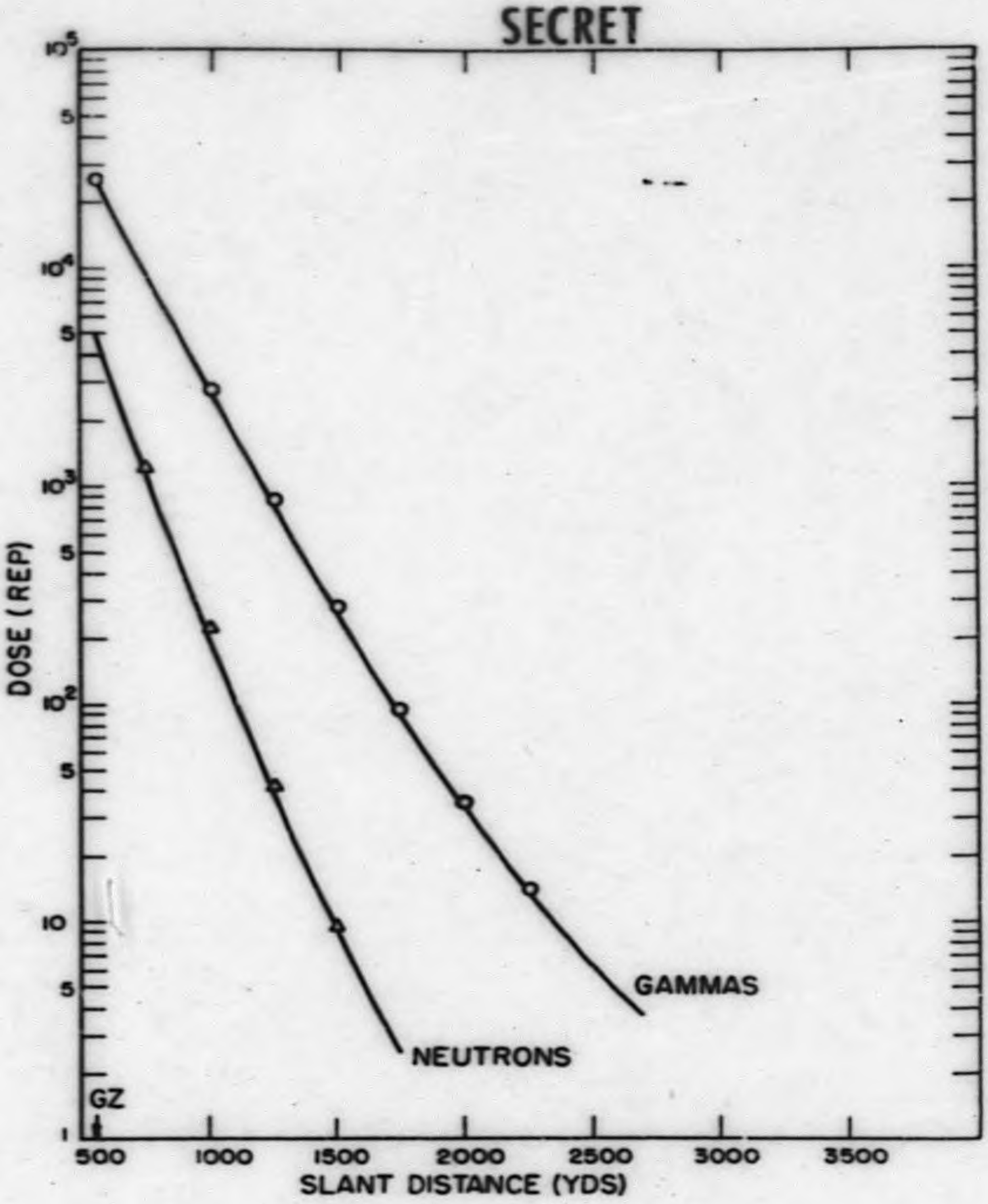

Fig. 9 Neutron and gamma radiation dose, in rep, versus distance (Nagasaki)

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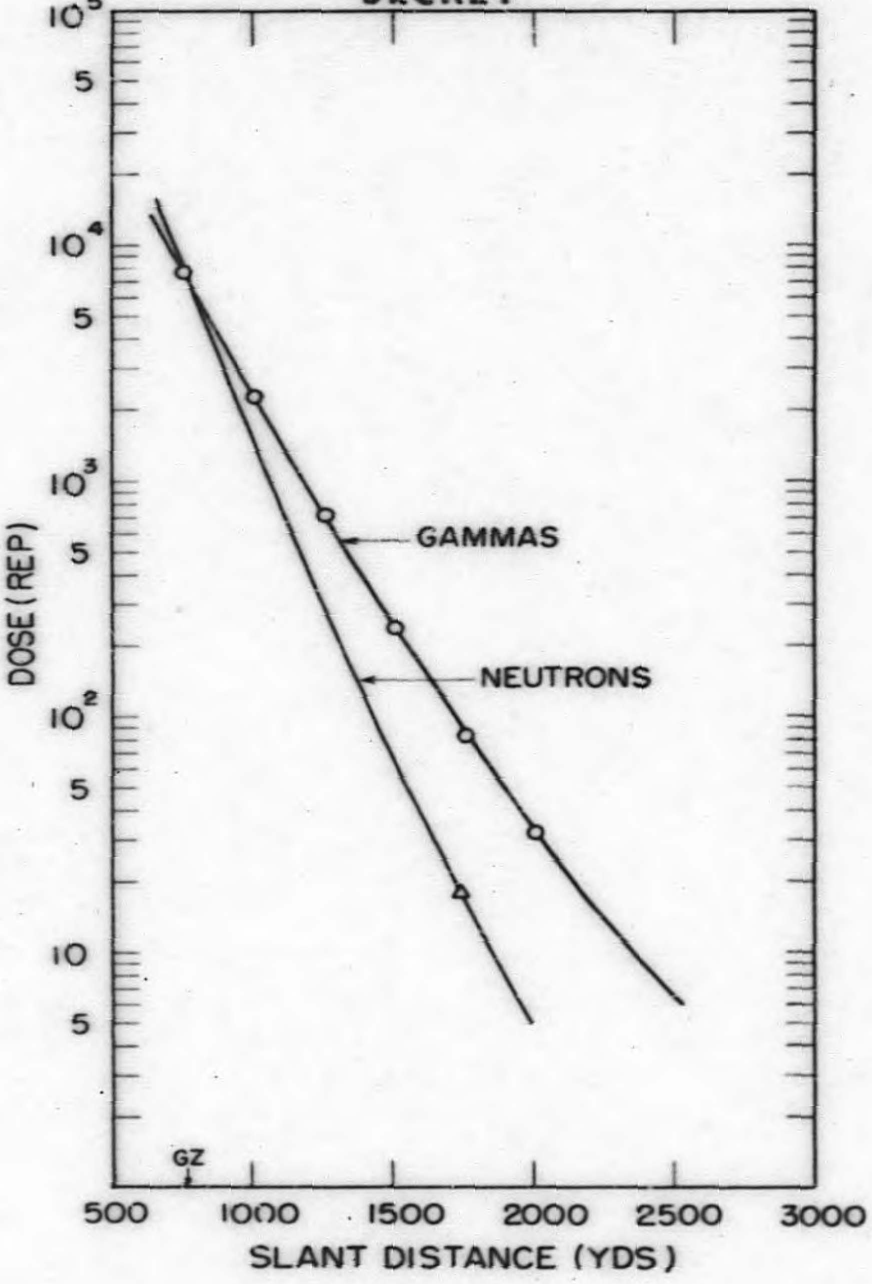

Fig. 10 Neutron and gamma radiation dose, in rep, versus distance (Hiroshima)

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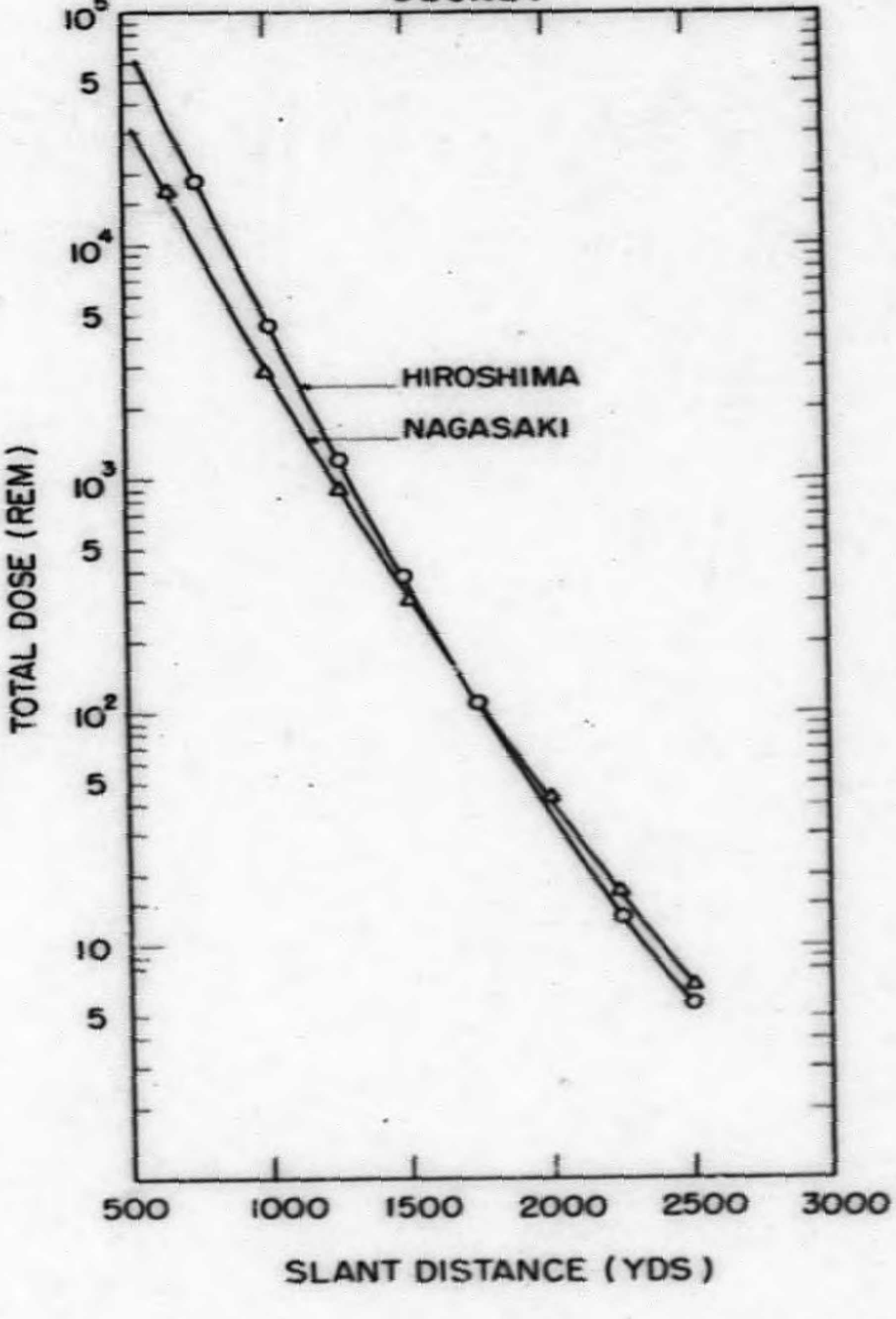

Fig. 11 Total radiation dose (rem) versus distance for the Japanese detonations

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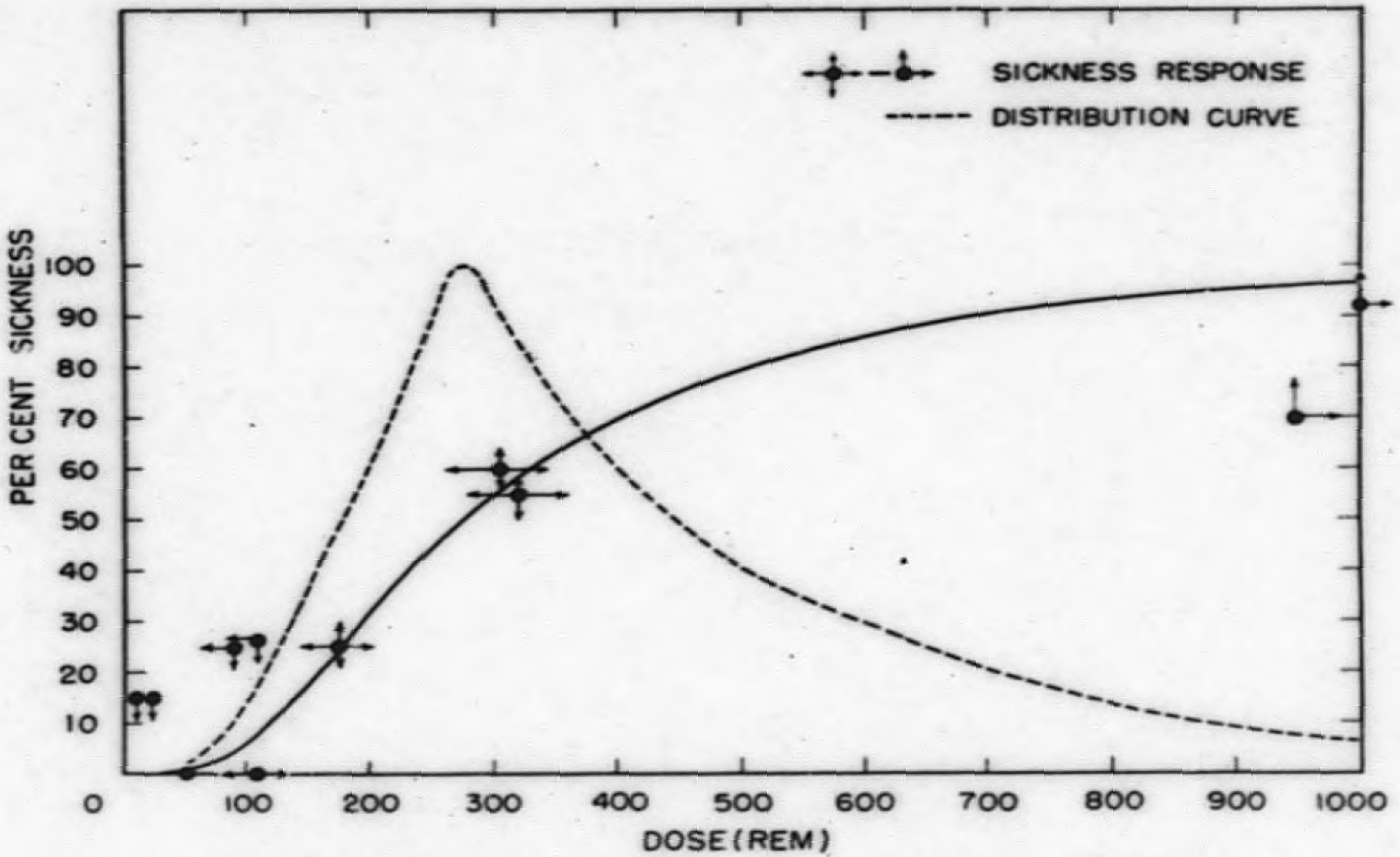

Fig. 12 Per cent acute sickness versus total radiation dose (rem) for a human population

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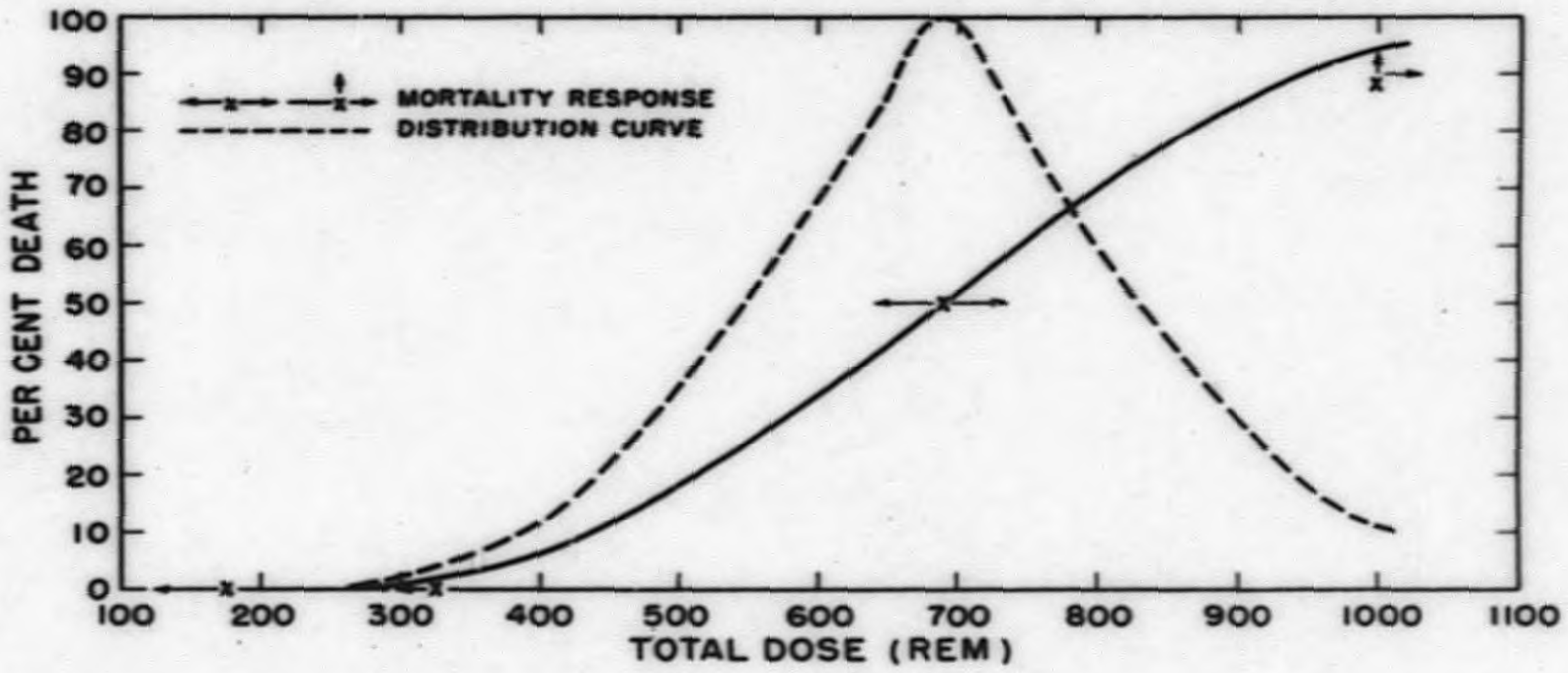

Fig. 13 Acute mortality versus total radiation dose (rem) for a human population

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