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EGH/jt

20 June 1946

MEMORANDUM

To: Lt. Colonel Leigh C. Fairbank, Corps of Engrs.
Military Operations Division, Manhattan Project
Headquarters, War Department, P. O. Box 2610,
Washington, D. C.

Subj: Measurement of the residual radiation intensity at the Hiroshima and Nagasaki atomic bomb sites, report on, forwarding of.

Ref: (a) Your memo to Captain Hakansson, dated 17 Jun 46.

1. In accordance with your request contained in reference (a) the subject report and a chart showing the Nagasaki bomb effect area are forwarded herewith.

2. You will note that this report has been classified SECRET by this Institute. A classification to TOP SECRET was considered indicated by Captain George M. Lyons, (MC), USNR, and the matter referred to the appropriate authority for action. No information on its final classification has been received.

3. Acknowledgment of receipt of subject report is requested.

E. G. Hakansson

E. G. HAKANSSON,
Captain, (MC), U. S. Navy,
Commanding.

Encls.(HW)
1. Subject report (1)
2. Chart (1)
3. Receipt (1)

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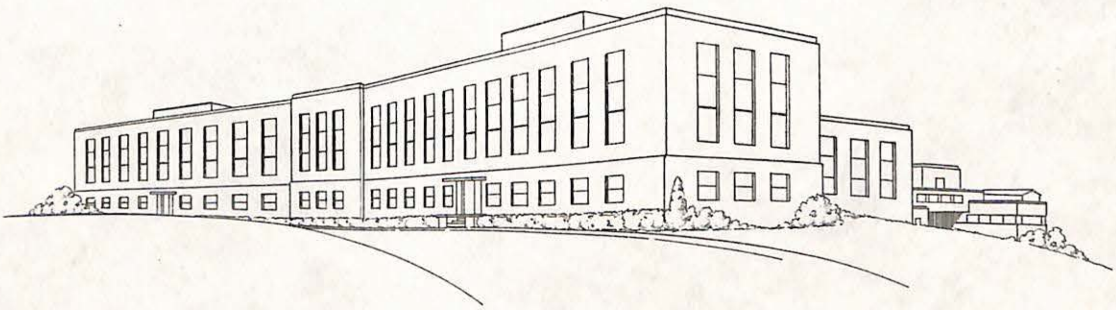

SECRET

MEASUREMENT OF THE RESIDUAL RADIATION
INTENSITY AT THE HIROSHIMA AND
NAGASAKI ATOMIC BOMB SITES

NMRI-160A

S E C R E T

NAVAL MEDICAL RESEARCH INSTITUTE
NATIONAL NAVAL MEDICAL CENTER
BETHESDA, MARYLAND

16 April 1946

MEASUREMENT OF THE RESIDUAL RADIATION INTENSITY AT THE HIROSHIMA AND NAGASAKI ATOMIC BOMB SITES

NMRI-160A

SUMMARY

1. Measurements of the residual radioactivity at the Hiroshima and Nagasaki atomic bomb sites were made by means of a portable Geiger-Müller counter during the period 70 to 100 days following the explosions. Most of the measurements were made at Nagasaki; those at Hiroshima being made only on the 87th and 88th days following the explosion there.

2. A series of maps is presented giving the results of this study. A characteristic feature of each of these explosions was that two distinct areas of residual activity were produced; an approximately circular area 600 to 1000 meters in radius about the point on the ground directly beneath the point of explosion in the air, and an elongate bilaterally symmetrical area of residual activity starting approximately 2 kilometers downwind from the hypocenter. The former area of residual activity is believed to have been caused primarily by the intense neutron bombardment of the ground, resulting in radioactive isotope transformation of several of the elements present in the earth. The downwind area of activity is believed to be the result primarily of deposition of fission products from the radioactive cloud which is known to have passed over the area under consideration.

3. Equations are given describing approximately the intensity of the residual radioactivity as a function of distance from the explosion center for the central areas at Hiroshima and Nagasaki. The intensity of residual activity, even at the hypocenter of these areas, was found to be far below the dose necessary to produce perceptible physiological effects. The highest values recorded were 70 to 80 micro-roentgens per hour.

4. A striking difference was noted, however, between the downwind areas at Hiroshima and Nagasaki. At Hiroshima the maximal residual activity observed in the downwind area was slightly less than that in the central area. At Nagasaki, on the other hand, downwind near the small village of

Nishiyama, a maximal value of 1080 micro-roentgens per hour was recorded. This value approaches the magnitude of the maximal tolerance dose of 4200 micro-roentgens per hour. It is believed that the difference between the downwind areas at Hiroshima and Nagasaki might be due to the fact that a different type of bomb was employed at each city.

5. In order to determine the effect on exposed personnel of the relatively high residual activity in the Nishiyama area, blood studies and case histories were obtained on a group of 60 inhabitants of Nishiyama 100 days following the explosion. The topography of the region is such that the village was in the shadow of a ridge with respect to the explosion proper and yet is in the area of maximal residual activity. The blood findings and histories of the inhabitants were normal.

6. A group of Japanese investigators from the Kyushu Imperial University made a similar study on the inhabitants of Nishiyama three times during October 1945 on days 53, 67, and 80 following the explosion. It was possible to study 25 individuals of their series 100 days following the explosion. A plot of the composite data reveals that a significant peak leucocytosis occurred in these individuals 70 to 80 days following the explosion. A mean leucocyte count of 16,200 per mm^3 was observed at 80 days. Thus significant, although slight, physiological effects were produced. It was possible to estimate the total integrated roentgen dosage received by the inhabitants of Nishiyama to be 56 roentgens. It would appear, therefore, that this quantity of radiation is capable of producing a measurable physiological change.

7. An equation was derived empirically giving approximately in roentgens the intensity of the radiation, producing radiation-sickness, released by the explosion of a plutonium bomb of the New Mexico type as a function of distance from the explosion. The radiation considered is of three types, gamma rays, fast neutrons, and slow neutrons. The equation follows:

$$I = \underbrace{\frac{2.72 \times 10^{9}\, e^{-0.0015x}}{x^2}}_{\text{(gamma rays)}} + \underbrace{\frac{4.84 \times 10^{9}\, e^{-0.00237x}}{x^2}}_{\text{(fast neutrons)}} + \underbrace{\frac{2.33 \times 10^{10}\, e^{-0.0078x}}{x^2}}_{\text{(slow neutrons)}}$$

I is the total radiation in roentgens at distance $\underline{x}$ in meters from the explosion. The equation is valid for distances greater than 800 meters, and gives low values at shorter distances. A table is presented giving the radiation intensities calculated from the above equation for the Nagasaki explosion.

BACKGROUND

The atomic bombs exploded at Hiroshima on 6 August 1945 and at Nagasaki on 9 August 1945 liberated tremendous quantities of energy, both mechanical, in the form of the air blast, and electromagnetic, in the form of thermal and ionizing radiations. In addition, large numbers of high energy neutrons were released which formed artificial radioactive isotopes of elements of substances in their paths. Isotope production is also possible by gamma ray absorption. This, however, was estimated to be several orders of magnitude less than the isotope production by neutron capture.

As a consequence of the explosions, a residual radioactivity was induced in the areas of Hiroshima and Nagasaki. The residual activity probably resulted from one or both of two causes: (a) the production of radioactive isotopes in the ground materials by the extremely intense neutron and gamma ray production incident to the explosion, and (b) the deposition on the ground of radioactive explosion products, e.g., fission products.

The purpose of this investigation was to make physical measurements and computations of the intensity and distribution of the residual activity, and to determine its relation to possibly harmful physiological effects.

METHOD

Measurements of the residual activity were made by means of the Naval Research Laboratory Portable Radioactivity Dosage Meter*, employing a self-quenching copper cathode Geiger-Müller counter tube. The counter was calibrated in terms of micro-roentgens per hour (μr/hr.) against 24.35 mg. of radium enclosed in a platinum capsule of 0.5 mm. wall thickness. It was assumed that 1 mg. radium through 0.5 mm. of platinum produces 8.4 r/hr. at a distance of 1 cm. Thus the radium standard used to calibrate the counter was assumed to produce 204.5 r/hr. at 1 cm. The radiation intensity at various distances was calculated by the formula:

$$I = \frac{I_o e^{-\mu x}}{x^2} \qquad (1)$$

where I is the r/hr. at distance x cm.

I_o = 204.5 r/hr.

μ = 4.64 x 10^{-5} (for gamma radiation from Radium C through air at 15° C.)

*The counter was constructed by Lt. (jg) M. Eicher, H(S), USNR, under the supervision of Dr. H. Friedman and his staff at the Naval Research Laboratory, Anacostia, and was modified by Captain D. L. Collins, AUS, of the Manhattan District.

Meter readings at various distances from the standard were plotted against the calculated radiation intensities for those distances, and the resulting curve was used to convert meter readings obtained in the field into $\mu r/hr.$ values. The sensitivity of the counter varied from day to day so that frequent re-calibration was necessary. In general, however, the sensitivity remained constant during a given sequence of measurements. During use in the field the counter was placed at a fixed distance of one meter above the ground by means of a suitable rigid support. A few measurements were also made with the counter 5 cm. above the ground.

Whenever possible the location of each point of measurement was accurately fixed on aerial photo mosaics of the area being surveyed. When photographs were not available, positions were plotted on maps. Adequate photo coverage was available for most of the Nagasaki measurements. The survey comprised about 1000 individual measurements, 900 in the Nagasaki area and 100 in the Hiroshima area. Earth samples were collected in many locations for further study in the United States.

In addition to the physical measurements, a brief evaluation of the physiological effects of the residual radiation was made by obtaining case histories and blood studies on some 60 persons residing in the Nagasaki area of activity but who were not exposed to the bomb explosion proper.

RESULTS

The areas of residual activity at both Hiroshima and Nagasaki were found to be of two forms; a well-defined, roughly circular area about the hypocenter of the explosion, and a diffuse and generally larger bilaterally symmetrical area some distance downwind from the hypocenter. The term "center" will denote the exact site of the bomb explosion in the air above the ground, and the term "hypocenter" will denote the point on the surface of the ground directly beneath the explosion center. The geographical areas of residual activity about the hypocenters will be known as the Hiroshima center area and the Nagasaki center area, respectively. The geographical area of activity downwind from the hypocenter at Hiroshima, which exhibited the highest radiation values near the village of Takasu 3.2 kilometers west of the hypocenter, will be termed the Takasu area. The corresponding area at Nagasaki began near the Nishiyama Reservoir 2.7 kilometers east of the hypocenter and its area of maximal intensity will be termed the Nishiyama area.

The geographical distribution and intensity of the residual radioactivity at Hiroshima and Nagasaki are shown in a series of four maps. Figure 1 shows the distribution of the activity in the Hiroshima area and figure 2 shows the distribution in the Nagasaki area. Figures 3 and 4 show in more detail the distribution of the activity in the Nagasaki area, figure 3 stressing the Nishiyama area and figure 4 the center area.

It is to be emphasized that the values shown on all of these maps are for the dates indicated and that the activity is diminishing steadily. For purposes of comparison of time periods the convention is adopted of expressing time in terms of days following the explosion. In the case of Hiroshima this will be given as H + the number of days, and in the case of Nagasaki as N + the number of days. Table 1 is given for convenience in effecting this transformation. All dates given in the text, unless otherwise noted, are Japanese time.

As shown in figure 1, the central area of activity at Hiroshima on 1 November 1945 (H + 87) exhibited a maximum intensity of 81 μr/hr. and was roughly radially symmetrical about the hypocenter. The displaced area of radioactivity near the village of Takasu lay downwind along the path of the prevailing winds on the day of the explosion and probably represents the site of deposition of the radioactive fission products formed in the explosion process. The highest intensity recorded was 42 μr/hr. Therefore, the residual activity in the Hiroshima area as a whole was far below physiologically significant intensity.

In order to express the residual activity as a function of distance from the center each of the areas enclosed by the intensity contour lines was measured with a planimeter and a mean radius about the hypocenter was thereby obtained. It was assumed that the residual activity in the central area resulted largely from the neutron bombardment which occurred at the time of the explosion and that the activity induced reflected this neutron intensity. As a first approximation it might be expected that neutron intensity would follow the inverse square law and also that some attenuation would occur as a result of passage through air. The relationship of distance and neutron intensity, and hence residual activity, might be expressed by an equation of the type:

$$I = \frac{I_o \, e^{-\mu x}}{x^2}$$

where I_o is the hypothetical residual activity at the explosion site proper, and μ is an attenuation coefficient. Table 2 includes the data from which such an equation was empirically derived for the residual activity in the Hiroshima central area. The equation follows:

$$I = \frac{1.01 \times 10^8 \, e^{-0.00276x}}{x^2} \qquad (2)$$

Where I is the residual activity in μr/hr. and x is the distance from the air burst in meters. A height of 570 meters above the ground was assumed (1) for the point of explosion so that distance from the center could be computed from the distance from the hypocenter. The intensity values calculated from equation 2 agree fairly well with those actually observed, and attenuation coefficient, μ, should agree with that for the neutron intensity as a function of distance.

As may be seen in figure 2 the general pattern of residual activity at Nagasaki was similar to that at Hiroshima. The central area of activity at Nagasaki on 18 October 1945 (N+70) exhibited a maximum value of 72 $\mu r/hr.$, and the extent of the residual activity in the center area was comparable to that at Hiroshima. An area of residual activity displaced downwind approximately the same distance as at Hiroshima was found in the Nishiyama area in the direction of the winds prevailing on the day of the explosion. One important difference may be observed between the situation at Hiroshima and that at Nagasaki. The activity in the Nishiyama area at Nagasaki was considerably greater than that in the Takasu area at Hiroshima. Many values in excess of 800 $\mu r/hr.$ were obtained, and the highest value measured was 1080 $\mu r/hr.$ This difference may in part be due to the fact that the bomb exploded at Hiroshima was U^{235}, whereas the Nagasaki bomb was plutonium.

The activity in the Nishiyama area is almost certainly the result of fission products deposited from the cloud formed by the explosion. The weather at 1100 on 9 August 1945 at Nagasaki was clear and warm with a light west southwest wind of a velocity of 3 meters per second (2). Residents in the Nishiyama area tell of the cloud passing over the region and droplets of yellow-brown liquid falling after the explosion occurred. A range of hills is interposed between the Nishiyama reservoir and the explosion hypocenter (fig. 3), and the east side of the Nishiyama valley is well out of the direct line from the explosion center, yet relatively high residual radioactivity was observed in the area. Furthermore, definite traces of residual activity were detected on the Shimabara Peninsula (fig. 2) some 20 miles west of the Nagasaki hypocenter, and the Japanese reported traces of activity in Kumamoto some 50 miles west of the hypocenter.

Figure 3 indicates the relationship between the Nagasaki center area and the Nishiyama area more clearly. It may be seen that at the time of measurement the two areas were distinct. The 11 $\mu r/hr.$ contour represents the lowest activity which was significantly different from background by the instrument used in the study. Aside from the large difference in intensity of radiation noted in the two areas, certain other differences were observed. In the center area no difference in counter reading was detectable whether the counter was held 1 meter above the ground or 5 cm. above the ground. Furthermore, the counter tube was equipped with a bubble window for beta ray measurements, and only a slight increase in meter reading (not more than 5 per cent) was noted when the bubble window was exposed. In the Nishiyama area on the other hand, the meter reading was almost doubled when the counter was moved from 1 meter above the ground to within 5 cm. of the ground. On exposing the bubble window the reading could be increased by approximately 20 per cent, thus indicating appreciable beta ray activity in the Nishiyama area. Finally it was observed that some variation in radiation intensity occurred in the Nishiyama area depending on whether the counter was held over a relatively undisturbed area such as open fields, or over areas such as roads and well-used trails. The readings were consistently higher in the former case than in the latter.

The distribution of residual activity in the Nagasaki center area is shown in detail in figure 4. The contour lines were drawn on the basis of approximately 600 individual measurements in this area, and they may be seen to be roughly radially symmetrical, although not as clearly as in the Hiroshima center area. The departure from true symmetry may be explained in large part by the broken nature of the terrain in this area. It is believed that the elongated shape of the 69 μr/hr. contour is due to the fact that a hill, on which the Urakami Prison was located, is in that area. Likewise a smaller isolated 69 μr/hr. contour occurred on the side of a hill to the southeast of the hypocenter. It is readily seen that although one point may be further removed from the hypocenter than another point, the former may actually be closer to the center by being on a hill, and hence would be exposed to a higher intensity of incident radiation.

As discussed previously for Hiroshima it was again assumed that in the Nagasaki center area the residual activity resulted from neutron bombardment, and the relationship of residual activity to distance from the center could be expressed as a first approximation by the equation:

$$I = \frac{I_0 \, e^{-\mu x}}{x^2}$$

The data from which the constants for this equation were obtained are given in table 3, and the equation describing the relation between distance from the center and residual activity at Nagasaki follows:

$$I = \frac{5.24 \times 10^8 \, e^{-0.0070x}}{x^2} \qquad (3).$$

where I is the residual activity in μr/hr., and x is the distance from the center in meters. A height of 490 meters above the hypocenter was assumed for the center in this case (1). The calculated intensity values agree moderately well with those observed, and the I_0 and μ values are comparable with those calculated for Hiroshima.

Shown in figure 4 are also the various estimates of the exact location of the hypocenter, and these may be seen to fall within a reasonable cluster. The "sight center" was located by sighting along fallen tree trunks around the periphery of the explosion area, and plotting the intersection of the cross bearings obtained by means of a transit. This hypocenter falls within the zone of highest residual activity. The Japanese group from the Kyushu Imperial University estimated the "Shinohara center" from their residual activity measurements, and the "Japanese center" was estimated by a Tokyo group from triangulation studies of the physical damage. These hypocenters also fall within the area of highest residual activity.

Of all the four areas exhibiting residual activity at Hiroshima and Nagasaki only one appeared to possess activities of physiological significance, namely the Nishiyama area. By chance the small village of Nishiyama, comprising several hundred in population, was situated along the west shore of the reservoir. As may be seen in figure 3 this location is very near the region of highest activity. It exhibited a mean radiation intensity of 700 $\mu r/hr.$ on N + 96, and was also out of direct line of the explosion. In view of these conditions the population of Nishiyama represented an ideal group for observation of the effects of the residual activity uncomplicated by the immediate effects of the explosion. It was possible to obtain case histories and blood studies on 60 men, women, and children in Nishiyama and a summary of the blood findings is presented in table 4*. It may be seen that on 16 to 19 November 1945, approximately 100 days following the explosion (N+99 to N+102), the blood picture was essentially normal. The mild normochromic normocytic anemia was apparently not unusual in the Japanese rural population, and this is likewise true of the mild eosinophilia. However, a group of Japanese investigators from the Kyushu Imperial University had obtained leucocyte counts from the inhabitants of Nishiyama on 1 October, 15 October and 28 October 1945, representing respectively N + 53, N + 67, and N + 80. It was possible to identify 25 persons in their series with corresponding persons in the series examined at N + 100. These data are given in table 5, and a variation in mean leucocyte count with time is plotted in figure 5. It may be seen that a significant peak leucocytosis occurred 70 to 80 days following the explosion, but that the condition had regressed 100 days following the explosion. A wide individual variation in the response was characteristic as indicated by the large increase in standard deviation. The case histories yielded no further significant findings. The temporary leucocytosis at about three weeks indicates that the maximal tolerance dose of radiation was exceeded for a sufficient length of time in Nishiyama to produce significant physiological effects, but that it fell below the maximal tolerance dose fairly quickly.

In the Nagasaki central area, six to 12 weeks after the explosion, interviews with residents revealed that a considerable number of them had re-entered the area within a day or two following the explosion, having been fortunate enough to be away on that day. Many of these persons had rebuilt their homes and replanted their small truck gardens, and careful questioning could elicit no subjective symptoms that might be associated with the bomb or its after effects. In fact, an almost invariable result of the questioning was the voluntary information that the truck gardens were considerably more fertile than before the explosion. It seemed remarkable that the average Nagasaki resident apparently viewed the atomic bomb as merely another implement in the armamentarium of war and did not appreciate its full import.

*Thanks are due Major S. Berg, AUS, under whose guidance the laboratory studies were made, and to W. Blagg, CPhM, USN, M. Saltsman, PhM2c, USNR, J. J. McManus, PhM2c, USNR, and T. C. Lohnes, PhM2c, USNR, for the actual determinations.

DISCUSSION

In order to obtain measurements of the residual activity at a later date, permission was obtained for two groups of Japanese scientists from the Kyushu Imperial University and the Tokyo Institute of Physics and Chemistry to make such observations at Hiroshima and Nagasaki. Their findings are reported separately (3,4), and half-life estimates for the residual activity at Nagasaki and Hiroshima were obtained. The best estimate for the half-life at the Hiroshima center area on 7 February 1946 (H+185) appears to be between 180 and 300 days (3). The half-life at the Nagasaki center area on 28 October 1945 (N+80) according to the Kyushu group (5) was 70 days, and on 23 December 1945 (N+136) according to the same group (4) it was 90 days. According to the calculations in table 6, which were based on composite data, on 27 December 1945 (N+140) the Nagasaki center area exhibited a half-life of 82 to 260 days, mean 146 days, depending on the distance from the hypocenter. It is of interest that according to calculations of the Japanese (3) for Hiroshima the half-life increases with distance from the hypocenter, whereas from table 6 it is seen that the reverse is true at Nagasaki. The meaning of this variation is not clear, and the variation may not be real. Japanese estimates are also available for the half-life of the activity in the Nishiyama area (4,5). On 28 October 1945 (N+80) the half-life was estimated to be 44 days, and on 23 December 1945 (N+136) it was 90 days.

It is clear that the half-life of the residual activity at both Hiroshima and Nagasaki is steadily increasing as the intensity of the radiation is decreasing with time. This is in accord with the well-recognized phenomenon of decay of mixtures of radioactive substances. As the shorter half-life components disappear, the over-all half-life of the mixture approaches that of longest half-life component present. This is undoubtedly the case in Hiroshima and Nagasaki.

The rate of decay of complex mixtures of radioactive substances may be expressed by the general equation:

$$I_o = I\,t^n \qquad (4)$$

where I_o may be considered in this case to be the radiation intensity in roentgens per hour (r/hr.) at one hour following the explosion, I the intensity in r/hr. at t hours following the explosion, and n as a specific decay constant. Through the courtesy of Dr. Joseph Hoffman, the value for n for the downwind cloud track at New Mexico was estimated at 1.21. It is assumed that the same value for n obtained in the Nishiyama area at Nagasaki.

As stated earlier, measurements at the village of Nishiyama on 13 November 1945 (N+96) yielded values of approximately 700 μr/hr. for the residual radiation intensity. Substituting the values for I, t, and n in equation 4 yields the value I_o as follows:

$$I_o = 7.0 \times 10^{-4}\ \text{r/hr.}\ (96\ \text{days} \times 24\ \text{hr/day})^{1.21} = 8.7\ \text{r/hr.}$$

Therefore, the time intensity relationship for the village of Nishiyama may be expressed by the equation:

$$I = 8.7\ t^{-1.21} \tag{5}$$

or

$$\log I = 0.9395 - 1.21 \log t \tag{6}$$

Solution of equation 6 for t when the intensity reached 0.1 r/hr. yields a value of 554 hours. Thus, the residual intensity at Nishiyama was above the maximal tolerance dose for approximately 23 days. In order to estimate the total roentgen dosage received by the inhabitants of this area, the time intensity curve was integrated. The simplifying assumption was made that because of time lag in the transport of the cloud by the wind and for the condensate to fall from the cloud, the radiation intensity on the ground at Nishiyama was zero for six minutes (0.1 hr.) following the explosion, and then the intensity rose instantly to its full value at six minutes. This obviously is an idealized representation; however, it serves as an approximation. Thus a total r dosage for Nishiyama may be computed by integrating equation 5 between the limits of 0.1 hour and 554 hours.

$$\int_{0.1}^{554} I\,dt = 8.7\left(\frac{t^{-0.21}}{-0.21}\right)\Bigg|_{0.1}^{554} = 56.1\ r$$

From this value it may be concluded that a total dosage of 56 r received over a period of 23 days is sufficient to produce a significant leucocyte response. There is some question as to whether the leucocytosis represents a primary stimulatory response to the radiation, or whether it represents a compensatory rise following a period of leucopenia. However, in view of the lag in the leucocyte response the latter conjecture would appear to be favored. The summated roentgen dosage received by the inhabitants of Nishiyama is plotted in figure 5, and it may be seen that the bulk of the total roentgens was received in the first few days following the explosion. Unfortunately, blood studies are not available for the first 53 days following the explosion, so that only a tentative conclusion concerning blood changes during this period can be drawn.

Data of the Tokyo group (6) concerning the distribution of residual activity about the hypocenter in the Nagasaki center area on N + 140 was analyzed as a function of distance from the center. A conversion factor of 1 J = 1.726 μr/hr. was used to convert their intensity values, and the treatment of the data is shown in table 7. The constants of the empirically derived equation were found to be closely similar to those obtained in equation 3 for this relationship at N + 70. The equation for t = N + 140 follows:

$$I = \frac{9.73 \times 10^{8}\ e^{-0.0086x}}{x^2} \tag{7}$$

where I is the residual activity in $\mu r/hr.$, and x is the distance from the center in meters.

In view of the wide divergence in technic of measurement and of the variability of the intensities owing to differences in terrain, the agreement between equations 3 and 7 is very good. Such agreement tends to substantiate the original assumption that the residual activity reflects the original neutron intensity occurring as a result of the explosion.

To further substantiate this view it was possible to derive equations describing the intensity of radioactivity induced in human bone and in elemental sulfur as a function of distance from the explosion center at Hiroshima. The original data were obtained from the report of Yamasaki and Sugimoto (7), and these data together with the fitted curves are shown in figures 6 and 7. The radioactivity induced in bone is due to the capture of slow neutrons by phosphorus, yielding P^{32} by the reaction $P^{31}(n\gamma)P^{32}$. The radioactivity induced in sulfur is due to the capture of fast neutrons by the sulfur with the loss of a proton, yielding P^{32} by the reaction $S^{32}(np)P^{32}$.

The equation for the activity of bone as a function of distance was found to be:

$$I = \frac{6.9 \times 10^{9}\, e^{-0.0078x}}{x^{2}} \qquad (8)$$

where I is the number of beta particles x 10^{-3} emitted per minute per gram of bone corrected to 6 August 1945, and x is the distance from the center in meters.

The equation for the activity of sulfur as a function of distance was found to be:

$$I = \frac{3.47 \times 10^{6}\, e^{-0.00237x}}{x^{2}} \qquad (9)$$

where I is the number of beta particles x 10^{-3} emitted per minute per gram of sulfur corrected to 6 August 1945, and x is the distance from the center in meters.

There is striking agreement between the attenuation coefficients (μ values) in equations 8 and 9, and the coefficients in equations 2, 3, and 7. Thus, the assumption that the distribution intensity of residual activity mirrors the distribution of neutron intensity produced by the blast is still further strengthened.

An attempt can now be made to approximate the relationship between neutron intensity and distance at the time of the explosion, and then to express the neutron intensity in terms of roentgen units so that the biological effects may be estimated. It is convenient to separate the neutrons into two categories, slow and fast, and for the present purposes slow neutrons are considered to have a mean energy of 200 electron volts, and fast neutrons of greater than 3 million electron volts. Finally, the relationship between gamma radiation intensity and distance from the explosion may be approximated and expressed in terms of roentgens, and the bulk of the radiation responsible for the production of radiation sickness may thus be accounted for.

The fast neutrons are considered first. According to a Manhattan District Project Report by Klema (8), a total of 6.5×10^{21} fast neutrons (energies above 3 Mev) passed through a sphere 202 meters in radius in the New Mexico explosion. Such a sphere has a surface of 5.13×10^9 cm^2. Therefore, the intensity at 202 meters was 1.27×10^{12} fast neutrons/cm^2. As discussed previously, neutrons are expected, as a first approximation, to obey the inverse square law with the incorporation of an attenuation factor thus:

$$I = \frac{I_o e^{-\mu x}}{x^2} \quad \text{or} \quad I_o = \frac{I x^2}{e^{-\mu x}}$$

In this case, I is the fast neutron intensity, $1.27 \times 10^{12}/cm^2$, at distance x of 202 meters, and μ is considered to be the constant 0.00237 obtained from the analysis of the Japanese sulfur data previously discussed. Solution for I_o, the fast neutron intensity at 1 meter, gives a value of 8.37×10^{17} fast neutrons/cm^2. This value corresponds to the total number (1.05×10^{23}) of fast neutrons that passed through a sphere 1 meter in radius. It is of considerable interest at this juncture to note that the Japanese (4), on the basis of their residual activity measurements, are in agreement among themselves that the total number of fast neutrons liberated was 1×10^{23}.

The daily minimum tolerance dose of fast neutrons was estimated by Professor G. H. Dessauer of the University of Rochester as being 200 fast neutrons/cm^2/second. In one day, then, a total of $200 \times 60 \times 60 \times 24 = 1.728 \times 10^7$ fast neutrons/cm^2 may be tolerated, and this is equivalent to the roentgen tolerance limit of 0.1 r. Therefore, it may be said that 1 r = 1.728×10^8 fast neutrons/cm^2. Converting the neutron intensity value at 1 meter to intensity in terms of r, a value of 4.84×10^9 r is obtained, and this may be considered to be I_o. Using the value of 0.00237 for μ, the equation

$$I = \frac{4.84 \times 10^9 e^{-0.00237x}}{x^2} \qquad (10)$$

may be written where I is the number of r occurring at a distance of x meters from the explosion owing to fast neutrons.

The effect of slow neutrons may be expressed in like manner. According to two Manhattan District Project Reports (8,9) a total of 3.8×10^{24}

slow neutrons (mean energy 200 electron volts) passed through a sphere 1 meter in radius. Again it is of interest to note that the Japanese (4) have estimated the total number of slow neutrons to be 6×10^{24}. Since a sphere 1 meter in radius has a surface area of 1.26×10^5 cm², it is readily calculable that an intensity of 3.02×10^{19} slow neutrons/cm² occurred at 1 meter. Again according to Professor Dessauer, the daily minimum tolerance dose of slow neutrons was estimated to be 1500 slow neutrons/cm²/second. Thus in one day a total of $1500 \times 60 \times 60 \times 24 = 1.296 \times 10^8$ slow neutrons/cm² may be tolerated, and this value is equivalent to 0.1 r. Assuming the conversion factor $1\ r = 1.296 \times 10^9$ slow neutrons/cm², the slow neutron intensity at 1 meter may be expressed as 2.33×10^{10} r. Using this value as I_0, and the value for μ as 0.0078 which was obtained by analysis of the Japanese bone activity data, it is possible to write the equation:

$$I = \frac{2.33 \times 10^{10}\ e^{-0.0078x}}{x^2} \qquad (11)$$

where I is the number of r occurring at a distance of x meters from the explosion owing to slow neutrons.

The last major factor responsible for the production of radiation sickness is the gamma rays produced by the explosion of the bomb. The exact relation between gamma ray intensity and distance from the explosion has been formulated by Weisskopf (9), and includes several factors which are important at distances less than 800 meters, such as the secondary gamma ray production of the radioactive isotopes produced in the ground by the neutron bombardment. For the present purpose, however, it is possible to formulate a more simple relationship which will serve as an approximation for the longer distances, these being of more importance medically. Values for I_0 and μ were derived from the data in a Manhattan District Memorandum Report (10) for distances greater than 800 meters, and the relationship between gamma ray intensity in r units, I, and distance in meters from the explosion, x, may be expressed by the equation:

$$I = \frac{2.72 \times 10^{9}\ e^{-0.0015x}}{x^2} \qquad (12)$$

The value of 0.0015 for μ in equation 12 is somewhat lower than expected, and corresponds to an extremely penetrating gamma radiation of energy considerably in excess of one Mev. This value, however, was obtained empirically from the best data available, and may be modified by future findings.

The total radiation received immediately in the form of fast neutrons, slow neutrons, and gamma rays may be expressed in r units as a function of distance from the explosion by a summation of equations 10, 11, and 12 thus:

$$I = \underbrace{\frac{2.72 \times 10^{9}\ e^{-0.0015x}}{x^2}}_{\text{(gamma rays)}} + \underbrace{\frac{4.84 \times 10^{9}\ e^{-0.00237x}}{x^2}}_{\text{(fast neutrons)}} + \underbrace{\frac{2.33 \times 10^{10}\ e^{-0.0078x}}{x^2}}_{\text{(slow neutrons)}} \qquad (13)$$

where I is the radiation in r units received immediately at a distance of x meters from the explosion. This equation is valid for distances greater than 800 meters, and for distances less than 800 meters it yields minimal values for I. Figure 8 has been constructed from equation 13 to indicate graphically the contribution of each of the three factors to the total radiation emitted at the time of the explosion, and table 8 shows the relative importance of the three factors at various distances from the explosion center and hypocenter at Nagasaki.

Substantiation of equation 13 is expected to come from a study of the radiation effects observed in the bomb victims at Nagasaki, and some modification of the constants may have to be made. This study is being carried out under the supervision of Captain Shields Warren, (MC), USNR, and the results are to be reported later. In addition, correlated studies on the nature of the residual radioactive materials in the ground at Nagasaki and Hiroshima are being carried out in this laboratory and will be reported separately. Finally, estimates of the heat intensity as a function of distance at Nagasaki are being made in collaboration with the Bureau of Standards, and these results will also be reported separately.

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Table 1.- Conversion of Japanese and United States dates to number of days following the explosion at Hiroshima (H+) and Nagasaki (N+)

Date Jap	Date U.S.	H+	N+	Date Jap.	Date U.S.	H+	N+	Date Jap.	Date U.S.	H+	N+
6 Aug 45	5 Aug 45	0		21 Sep	20 Sep	46	43	6 Nov	5 Nov	92	89
7	6	1		22	21	47	44	7	6	93	90
8	7	2		23	22	48	45	8	7	94	91
9	8	3	0	24	23	49	46	9	8	95	92
10	9	4	1	25	24	50	47	10	9	96	93
11	10	5	2	26	25	51	48	11	10	97	94
12	11	6	3	27	26	52	49	12	11	98	95
13	12	7	4	28	27	53	50	13	12	99	96
14	13	8	5	29	28	54	51	14	13	100	97
15	14	9	6	30	29	55	52	15	14	101	98
16	15	10	7	1 Oct	30	56	53	16	15	102	99
17	16	11	8	2	1 Oct	57	54	17	16	103	100
18	17	12	9	3	2	58	55	18	17	104	101
19	18	13	10	4	3	59	56	19	18	105	102
20	19	14	11	5	4	60	57	20	19	106	103
21	20	15	12	6	5	61	58	21	20	107	104
22	21	16	13	7	6	62	59	22	21	108	105
23	22	17	14	8	7	63	60	23	22	109	106
24	23	18	15	9	8	64	61	24	23	110	107
25	24	19	16	10	9	65	62	25	24	111	108
26	25	20	17	11	10	66	63	26	25	112	109
27	26	21	18	12	11	67	64	27	26	113	110
28	27	22	19	13	12	68	65	28	27	114	111
29	28	23	20	14	13	69	66	29	28	115	112
30	29	24	21	15	14	70	67	30	29	116	113
31	30	25	22	16	15	71	68	1 Dec	30	117	114
1 Sep	31	26	23	17	16	72	69	2	1 Dec	118	115
2	1 Sep	27	24	18	17	73	70	3	2	119	116
3	2	28	25	19	18	74	71	4	3	120	117
4	3	29	26	20	19	75	72	5	4	121	118
5	4	30	27	21	20	76	73	6	5	122	119
6	5	31	28	22	21	77	74	7	6	123	120
7	6	32	29	23	22	78	75	8	7	124	121
8	7	33	30	24	23	79	76	9	8	125	122
9	8	34	31	25	24	80	77	10	9	126	123
10	9	35	32	26	25	81	78	11	10	127	124
11	10	36	33	27	26	82	79	12	11	128	125
12	11	37	34	28	27	83	80	13	12	129	126
13	12	38	35	29	28	84	81	14	13	130	127
14	13	39	36	30	29	85	82	15	14	131	128
15	14	40	37	31	30	86	83	16	15	132	129
16	15	41	38	1 Nov	31	87	84	17	16	133	130
17	16	42	39	2	1 Nov	88	85	18	17	134	131
18	17	43	40	3	2	89	86	19	18	135	132
19	18	44	41	4	3	90	87	20	19	136	133
20	19	45	42	5	4	91	88	21	20	137	134

Table 1 (Continued)

Date Jap.	Date U.S.	H+	N+	Date Jap.	Date U.S.	H+	N+	Date Jap.	Date U.S.	H+	N+
22 Dec 45	21 Dec 45	138	135	6 Feb	5 Feb	184	181	24 Mar	23 Mar	230	227
23	22	139	136	7	6	185	182	25	24	231	228
24	23	140	137	8	7	186	183	26	25	232	229
25	24	141	138	9	8	187	184	27	26	233	230
26	25	142	139	10	9	188	185	28	27	234	231
27	26	143	140	11	10	189	186	29	28	235	232
28	27	144	141	12	11	190	187	30	29	236	233
29	28	145	142	13	12	191	188	31	30	237	234
30	29	146	143	14	13	192	189	1 Apr	31	238	235
31	30	147	144	15	14	193	190	2	1 Apr	239	236
1 Jan 46	31	148	145	16	15	194	191	3	2	240	237
2	1 Jan 46	149	146	17	16	195	192	4	3	241	238
3	2	150	147	18	17	196	193	5	4	242	239
4	3	151	148	19	18	197	194	6	5	243	240
5	4	152	149	20	19	198	195	7	6	244	241
6	5	153	150	21	20	199	196	8	7	245	242
7	6	154	151	22	21	200	197	9	8	246	243
8	7	155	152	23	22	201	198	10	9	247	244
9	8	156	153	24	23	202	199	11	10	248	245
10	9	157	154	25	24	203	200	12	11	249	246
11	10	158	155	26	25	204	201	13	12	250	247
12	11	159	156	27	26	205	202	14	13	251	248
13	12	160	157	28	27	206	203	15	14	252	249
14	13	161	158	1 Mar	28	207	204	16	15	253	250
15	14	162	159	2	1 Mar	208	205	17	16	254	251
16	15	163	160	3	2	209	206	18	17	255	252
17	16	164	161	4	3	210	207	19	18	256	253
18	17	165	162	5	4	211	208	20	19	257	254
19	18	166	163	6	5	212	209	21	20	258	255
20	19	167	164	7	6	213	210	22	21	259	256
21	20	168	165	8	7	214	211	23	22	260	257
22	21	169	166	9	8	215	212	24	23	261	258
23	22	170	167	10	9	216	213	25	24	262	259
24	23	171	168	11	10	217	214	26	25	263	260
25	24	172	169	12	11	218	215	27	26	264	261
26	25	173	170	13	12	219	216	28	27	265	262
27	26	174	171	14	13	220	217	29	28	266	263
28	27	175	172	15	14	221	218	30	29	267	264
29	28	176	173	16	15	222	219	1 May	30	268	265
30	29	177	174	17	16	223	220	2	1 May	269	266
31	30	178	175	18	17	224	221	3	2	270	267
1 Feb	31	179	176	19	18	225	222	4	3	271	268
2	1 Feb	180	177	20	19	226	223	5	4	272	269
3	2	181	178	21	20	227	224	6	5	273	270
4	3	182	179	22	21	228	225	7	6	274	271
5	4	183	180	23	22	229	226	8	7	275	272

Table 2.- Calculation of equation for expression of residual activity at Hiroshima in terms of the distance from the air burst point (height assumed to be 570 meters) of the bomb. This equation is for the residual activity as of 1 November 1945, 87 days following the explosion (H + 87).

Distance, d, from hypo-center (meters)	Distance, x, from air burst point (meters)	x^2	Intensity, I, of residual activity (μr/hr.)	Calculated μ	Calculated I_0 (μr/hr.)	Calculated I (μr/hr.)*
73.4	574.7	330,288	69.3	--	1.12×10^8	62.6
130.4	584.7	341,900	57.3	0.00342	0.99×10^8	58.8
247.6	621.5	386,300	44.8	0.00209	0.96×10^8	47.0
379.8	684.9	469,050	32.0	0.00278	0.99×10^8	32.5
532.3	780.4	609,100	18.9	--	0.99×10^8	19.2
869.0	1039.3	1,080,060	10.7		---	5.3
			Mean	0.00276	1.01×10^8	

*Calculated from equation:

$$I = \frac{1.01 \times 10^8 \, e^{-0.00276x}}{x^2}$$

Where I is the residual activity in μr/hr.
and x is the distance from the air burst point in meters

Table 3.- Calculation of equation for expression of residual activity at Nagasaki in terms of the distance from the air burst point (height assumed to be 490 meters) of the bomb. This equation is for the residual activity as of 18 October 1945, 70 days following the explosion (N + 70)

Distance, d, from hypocenter (meters)	Distance, x, from air burst point (meters)	x^2	Intensity, I, of residual activity (μr/hr.)	Calculated μ	Calculated I_0 (μr/hr.)	Calculated* I (μr/hr.)
46.9	492.2	242,300	69.3			69.0
				0.01200	5.27×10^8	
118.2	504.1	254,070	57.3			60.5
				0.00983	4.96×10^8	
180.1	522.0	272,535	44.8			49.7
				0.00657	4.72×10^8	
260.0	554.7	307,700	32.0			35.1
				0.00297	4.78×10^8	
408.5	637.9	406,970	18.9			14.8
				0.00360	6.69×10^8	
534.1	724.9	525,470	10.7			6.2
			Mean	0.00700	5.24×10^8	

*Calculated from equation:

$$I = \frac{5.24 \times 10^8 \, e^{-0.0070x}}{x^2}$$

where I is the residual activity in μr/hr.
and x is the distance from the air burst point in meters

Table 4.- Summary of the blood findings on inhabitants of the village of Nishiyama approximately 100 days following the explosion (N + 99 to N + 102)

Variable examined	No. of cases	Range	Mean
Age in years	61	2 - 86	37.24
Erythrocyte count per mm^3	61	1,470,000 - 4,980,000	4,139,500
Hemoglobin, grams per 100 cc.	61	<7.0 - 14.2	12.0
Leucocyte count per mm^3	61	4,750 - 13,000	7,356
Differential leucocyte count			
Segmented neutrophiles, per cent	61	34 - 76	57.6
Lymphocytes, per cent	61	16 - 50	32.7
Monocytes, per cent	61	0 - 12	4.7
Eosinophiles, per cent	61	0 - 28	4.7
Basophiles, per cent	61	0 - 2	0.2
Hematocrit, per cent	28	32 - 43	37.2
Mean corpuscular volume, μ^3	28	70 - 107	89.1
Mean corpuscular hemoglobin, $\mu\mu$gm.	30	21 - 36	29.4
Mean corpuscular hemoglobin concentration, per cent	28	19.5 - 39	33.3
Volume index	28	0.80 - 1.24	1.034
Color index	30	0.73 - 1.12	1.032

Table 5.- Leucocyte counts of 25 residents of Nishiyama who were not exposed to the atomic bomb explosion but who resided in Nishiyama continuously since the explosion. The data on 1, 15, and 28 October 1945 (N + 53, N + 67, and N + 80) were obtained by Japanese investigators from the Kyushu Imperial University

Name	Age	Sex	Jap. No.	Leucocyte count/mm^3 N + 53 1 Oct 45	N + 67 15 Oct 45	N + 80 28 Oct 45	N 100 17 Nov 45
NAKAO Tsuki	65	F	124	6,800	16,400	10,600	9,000
NAKAO Takaichi	48	M	123	5,200	6,400	8,500	4,800
NAKAO Taka	41	F	135	11,600	14,800	12,000	10,000
NAKAO Taeko	18	F	122	17,000	23,100	25,000	8,800
NAKOA Tsunehisa	11	M	88	12,600	17,400	30,700	6,600
YAMAGUCHI Iwamatsu	68	M	-	8,200	8,700	13,500	6,200
NAKOA Eijiro	60	M	-	4,900	5,200	4,500	5,800
URAKAWA Kiichi	60	M	-	5,900	9,300	8,800	6,900
URAKAWA Gempachi	58	M	2	7,600	10,300	9,800	6,400
NAKAO Fumi	51	F	-	4,500	7,700	9,300	4,900
URAKAWA Suga	45	F	106	7,200	9,200	5,200	5,800
NAKOA Matsu	44	F	63	7,500	11,100	13,000	8,600
MATSUO Takisaburo	44	M	3	16,200	30,800	27,700	7,200
NAKAO Tsuta	41	F	13	11,400	37,800	36,300	8,400
HASHIGUCHI Chika	39	F	112	11,700	16,100	19,600	7,100
URAKAWA Torao	38	M	126	11,400	20,800	12,200	8,200
YAMAMOTO Harue	30	F	26	7,800	6,600	8,600	5,100
YAMAGUCHI Yoshino	25	F	121	6,500	12,100	20,000	6,200
NAKAO Masaka	25	F	105	12,400	18,900	23,400	11,500
NAKAO Kazuko	17	F	-	15,500	10,200	11,900	10,400
NAKAO Toshikazu	15	M	-	9,100	15,300	14,800	7,800
MATSUO Akira	14	M	-	8,200	13,200	18,900	6,100
OKAWACHI Masahiko	13	M	-	9,700	15,300	18,800	6,400
NAKAO Kiyoshi	11	M	-	12,600	17,400	30,700	7,500
MATSUO Tadayuki	7	M	-	8,300	15,900	10,800	6,800
N = 25			Mean	9,592	14,800	16,184	7,300
			S.D.	3,439	7,404	8,430	1,691

Table 6.— Calculation of half-life of residual activity at Nagasaki based on data obtained by NavTechJap Team 11-100 on 18 October 1945 (N + 70) and data obtained by Japanese investigators (6) on 27 December 1945 (N + 140)

Distance, d, from hypocenter (meters)	Distance, x, from air burst (meters)	Intensity, I_{70}, at N + 70* (μr/hr.)	Intensity, I_{140}, at N + 140** (μr/hr.)	λ	Half-life (days)
99.5	500	63.4	52.6	0.00267	259.6
249.8	550	36.9	28.3	0.00379	182.9
346.3	600	21.8	15.5	0.00487	142.3
427.1	650	13.1	8.5	0.00618	112.2
499.9	700	8.0	4.8	0.00730	95.0
567.8	750	4.9	2.7	0.00851	81.5
				Mean	145.6

*Calculated from equation:

$$I_{70} = \frac{5.24 \times 10^{8}\, e^{-0.0070x}}{x^{2}}$$

**Calculated from equation:

$$I_{140} = \frac{9.73 \times 10^{8}\, e^{-0.00861x}}{x^{2}}$$

where I = intensity of residual activity in μr/hr.

and x = distance from air burst point in meters (height of burst = 490 meters)

Table 7.- Calculation of equation for expression of residual activity at Nagasaki in terms of the distance from the air burst point (height assumed to be 490 meters) of the bomb. The equation is for Japanese residual activity data (6) as of 27 December 1945, 140 days following the explosion (N + 140)

Distance, d, from hypo-center (meters)	Distance, x, from air burst point (meters)	x^2	Intensity, I, of residual activity (μr/hr.)	Calculated μ	Calculated I_o (μr/hr.)	Calculated I* (μr/hr.)
62	493.9	243,944	56.6		9.69×10^8	56.8
				0.00676		
106	501.3	251,336	52.2		9.83×10^8	51.8
				0.00814		
163	516.4	266,669	43.5		9.90×10^8	42.5
				0.00742		
218	536.3	287,624	34.8		10.13×10^8	33.5
				0.00853		
271	559.9	313,541	26.1		10.15×10^8	25.1
				0.01153		
323	586.9	344,429	17.4		9.38×10^8	18.1
				0.00930		
415	642.1	412,325	8.7		9.03×10^8	9.4
			Mean	0.00861	9.73×10^8	

*Calculated from the equation:

$$I = \frac{9.73 \times 10^8 \, e^{-0.00861\, x}}{x^2}$$

where I is the residual activity in μr/hr.
and x is the distance from the air burst point in meters

Table 8.— Calculation, from equation 13, of the total radiation intensity, I, in roentgen units produced by gamma rays, I_{γ}, fast neutrons, I_{fn}, and slow neutrons, I_{sn}, as a function of the distance in meters, x, from the explosion center, at the time of the explosion at Nagasaki

Distance from hypo-center (meters)	Distance from center (x) (meters)	x^2	I_{γ} (r units)	I_{fn} (r units)	I_{sn} (r units)	Total I (r units)
500	700	490,000	1943	1880	202	4025
750	896	802,816	883	721	27	1631
1000	1114	1,240,996	413	278	3	694
1250	1343	1,803,649	201	111	1	313
1500	1577	2,486,929	103	46		149
1750	1816	3,297,856	54	20		74
2000	2059	4,239,481	29	9		38
2250	2303	5,303,809	16	4		20
2500	2549	6,497,401	9	2		11

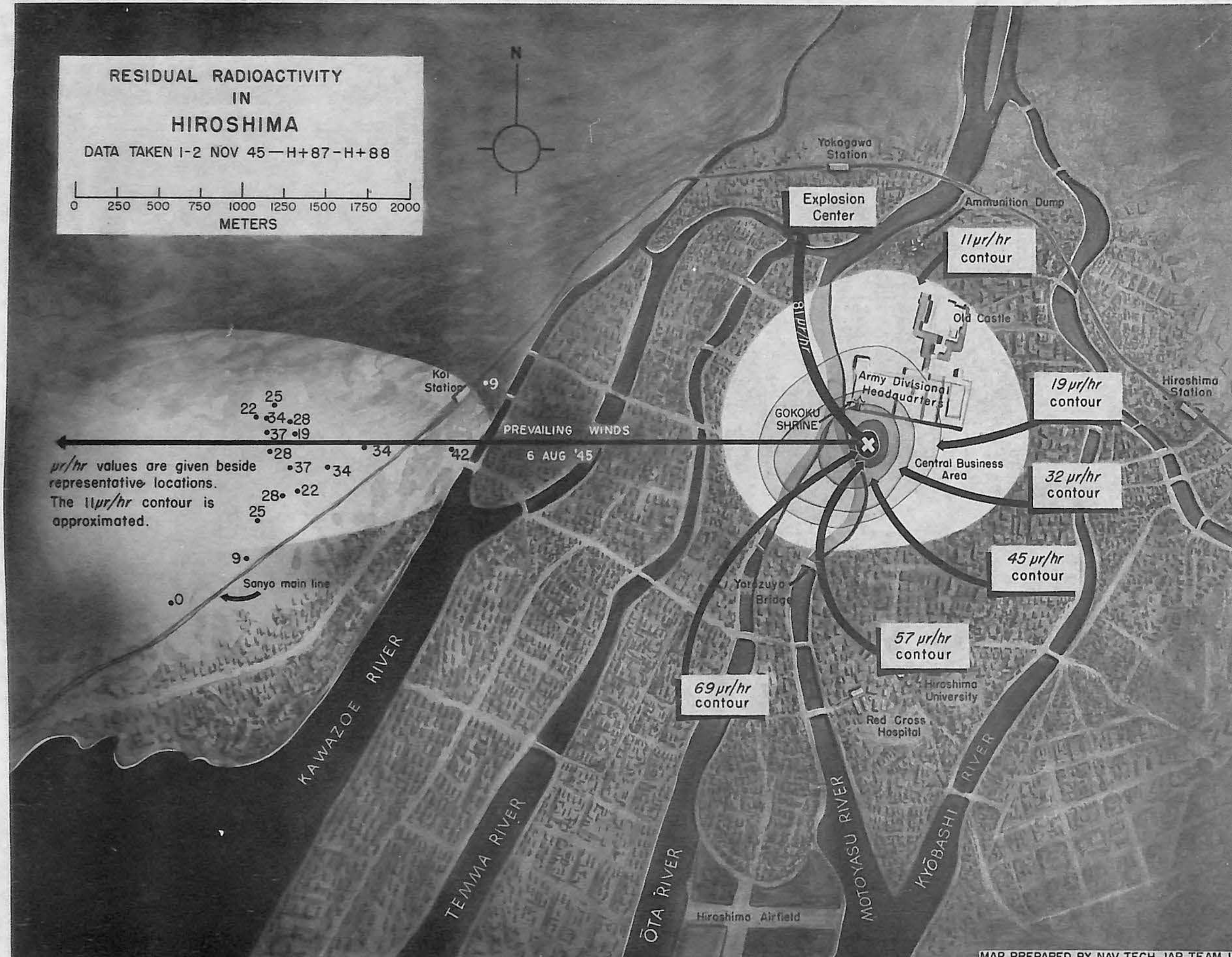
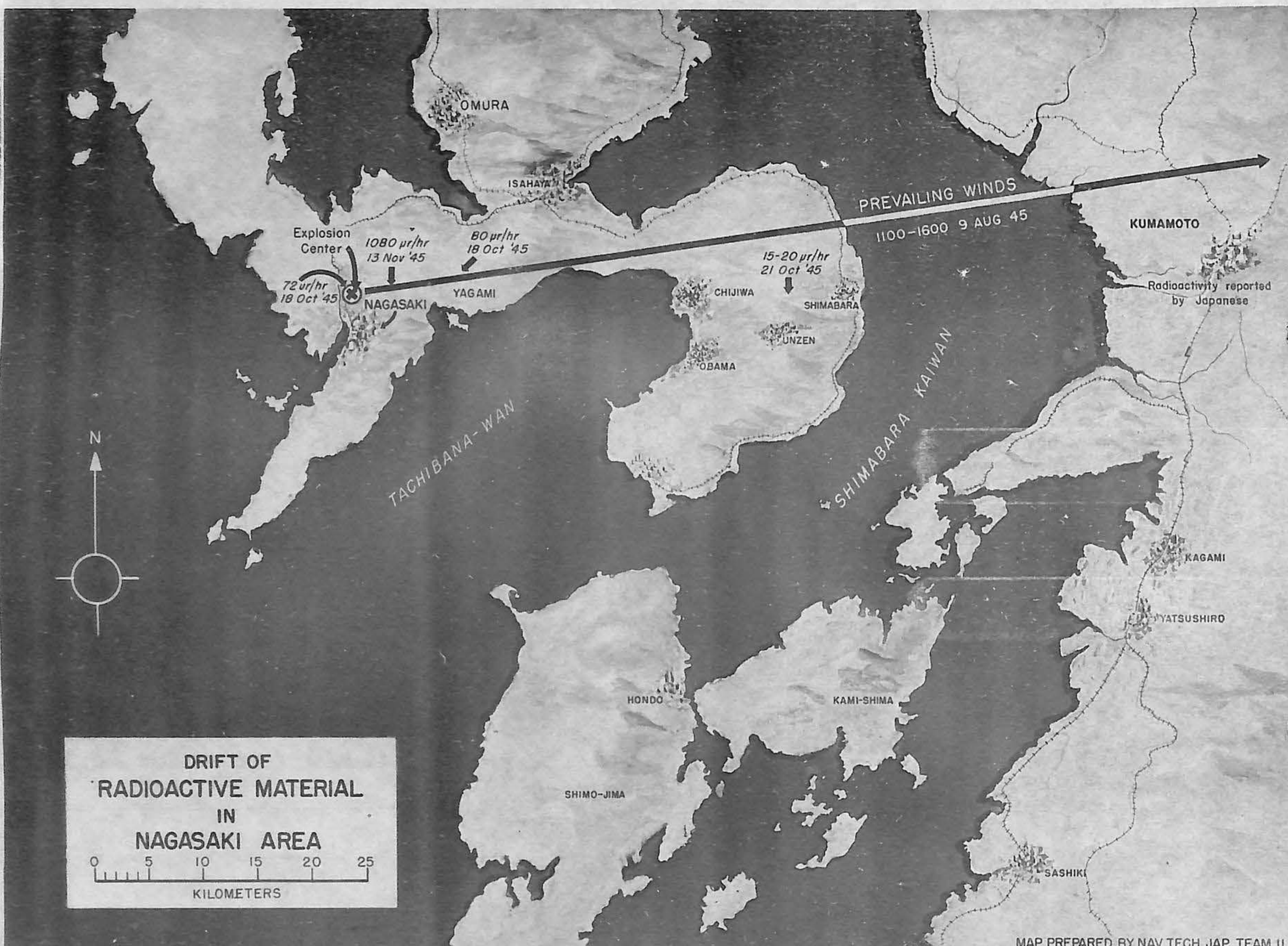


Figure 1

NMRI-HADDEN '46



NMRI-HADDEN '46

Figure 2

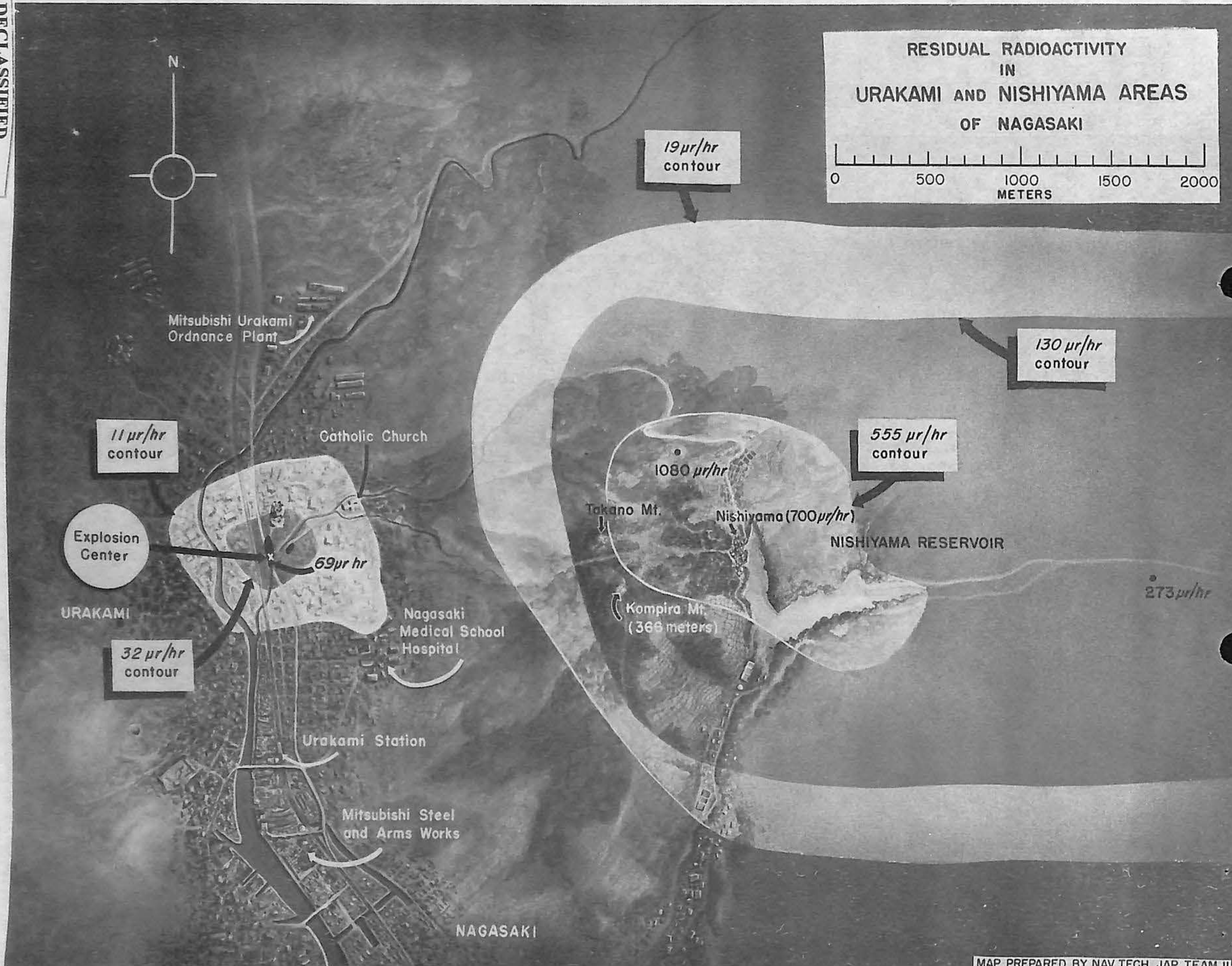


Figure 3

NMRI-HADDEN '46

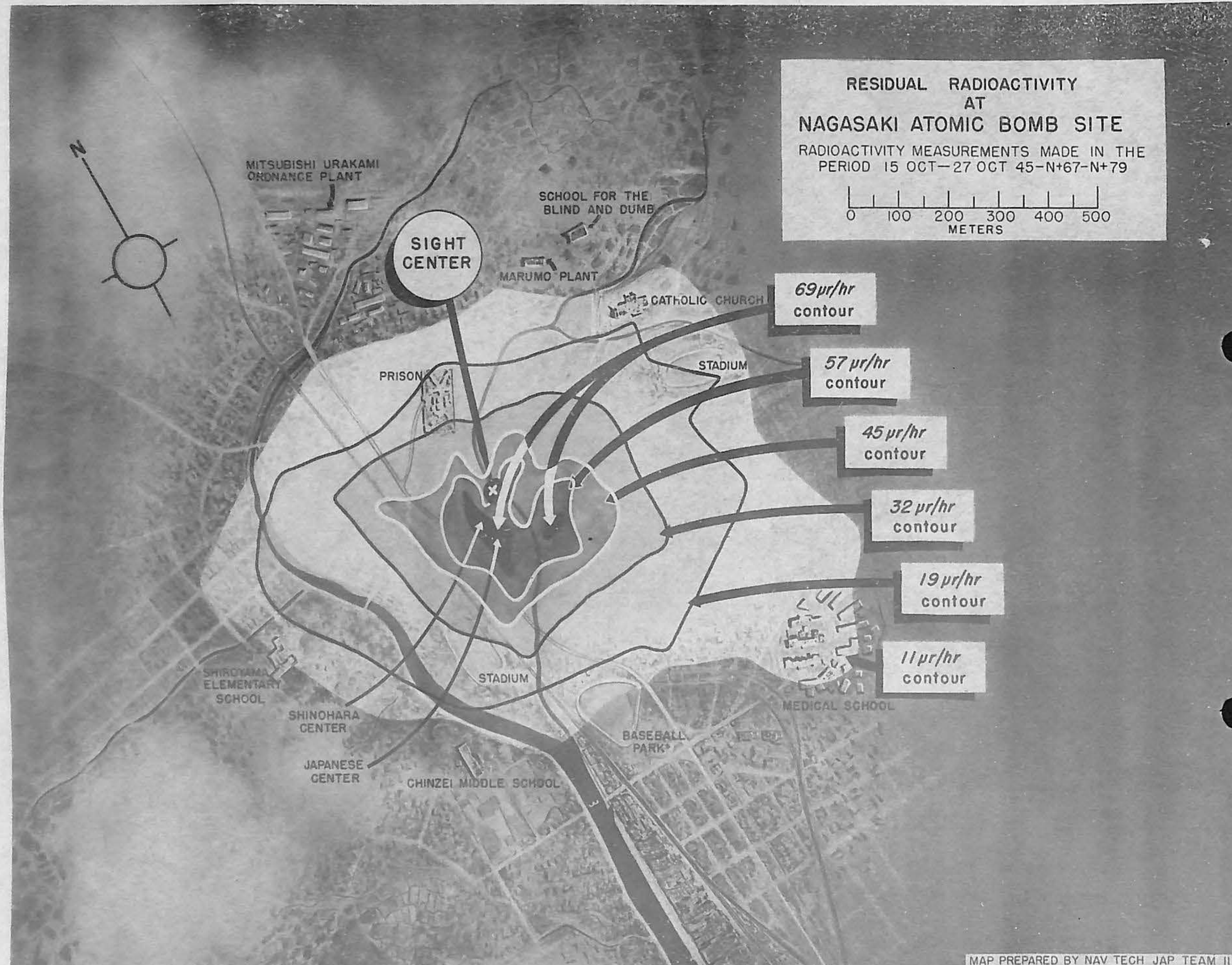


Figure 4

NMRI-HADDEN '46

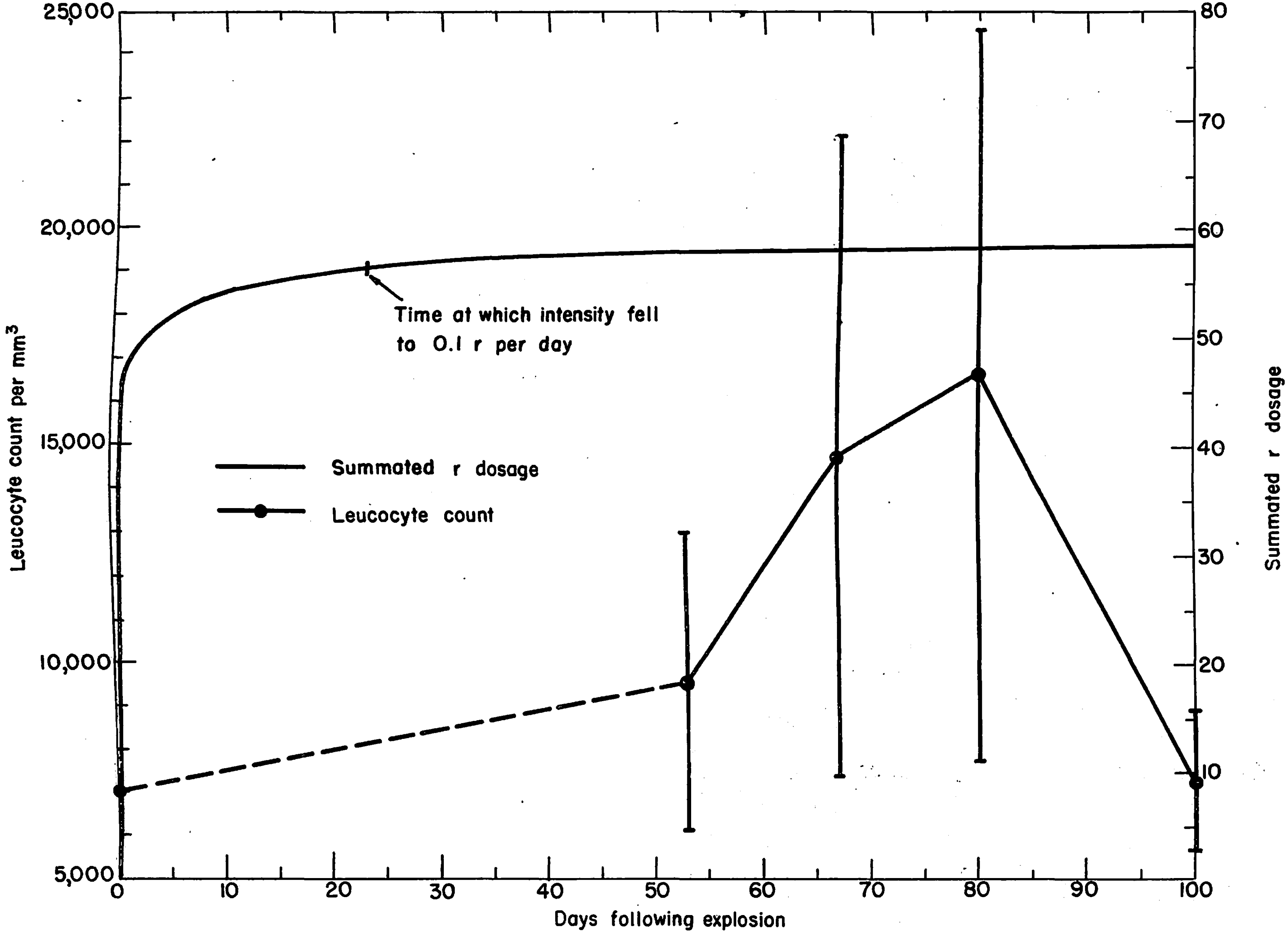


Figure 5.- Mean leucocyte count on 25 residents of Nishiyama and summated roentgen dosage received as a function of days following the Nagasaki atomic bomb explosion. The leucocyte data for days 53, 68 and 80 are from Japanese sources and the value at 0 days was assumed to be normal. The vertical bars represent plus and minus one standard deviation.

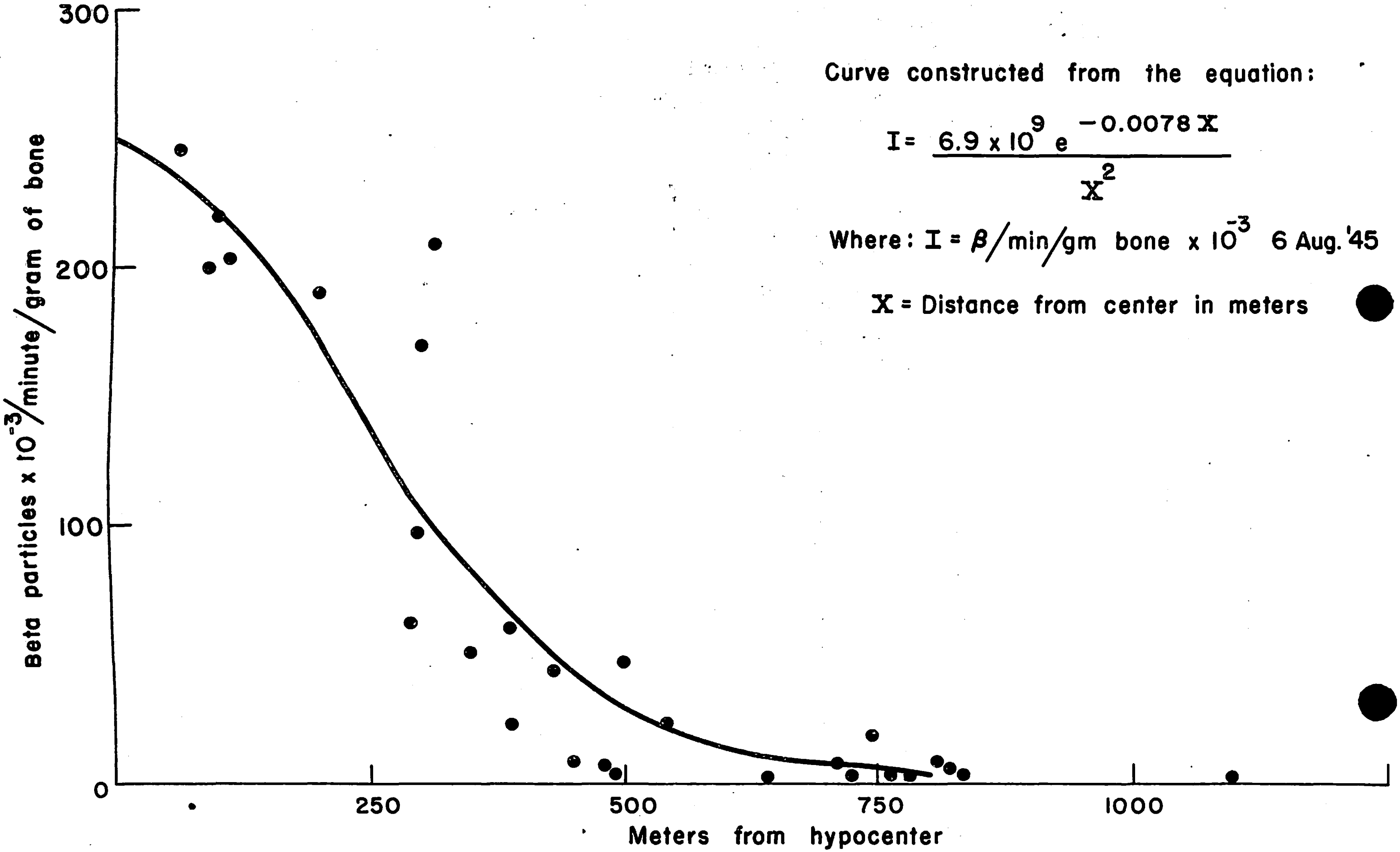


Figure 6.—Residual activity in bone at Hiroshima from data of Yamasaki and Sugimoto.

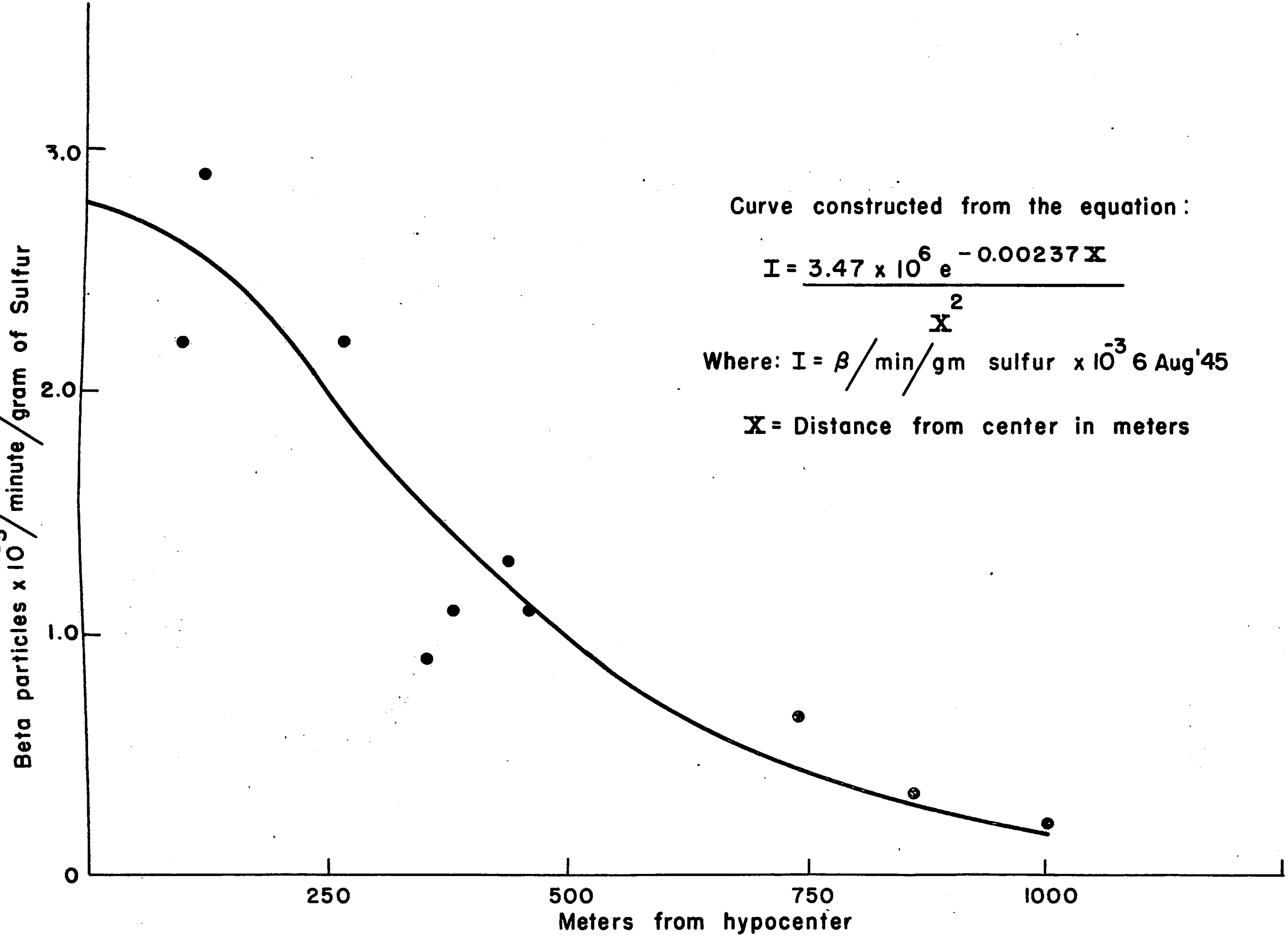


Figure 7.— Residual activity in Sulfur at Hiroshima from data of Yamasaki and Sugimoto.

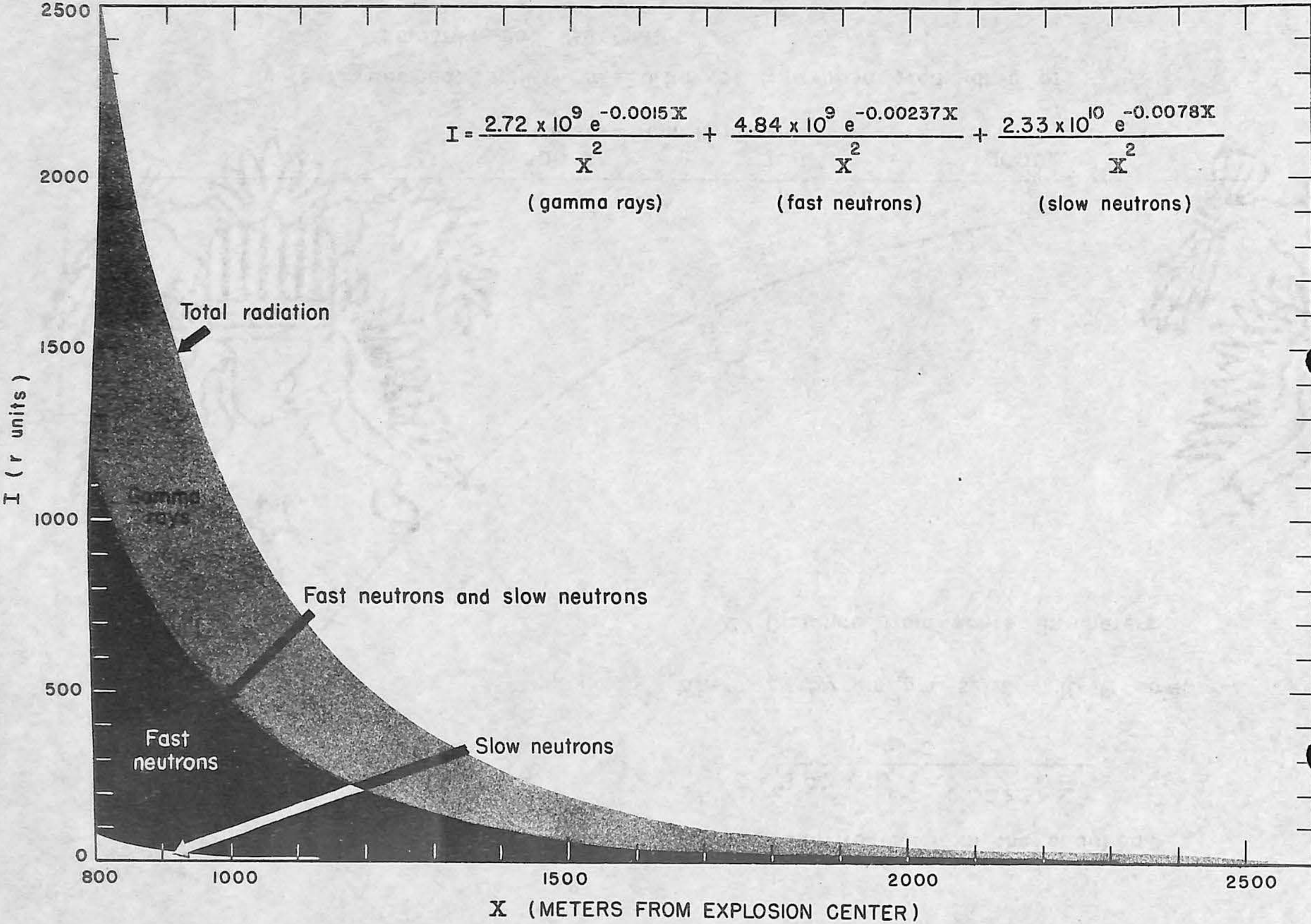


Figure 8.—Contribution of gamma rays, fast neutrons, and slow neutrons to the total roentgen dosage received immediately at various distances from the explosion of a plutonium bomb.