Chapter 1

BOMB PARAMETERS

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Introduction

The reconstruction of neutron and gamma-ray doses at Hiroshima and Nagasaki begins with a determination of the parameters describing the explosion. The calculations of the air transported radiation fields and survivor doses from the Hiroshima and Nagasaki bombs require knowledge of a variety of parameters related to the explosions. These various parameters include the heading of the bomber when the bomb was released, the epicenters of the explosions, the bomb yields, and the tilt of the bombs at time of explosion. The epicenter of a bomb is the explosion point in air that is specified in terms of a burst height and a hypocenter (or the point on the ground directly below the epicenter of the explosion). The current reassessment refines the energy yield and burst height for the Hiroshima bomb, as well as the locations of the Hiroshima and Nagasaki hypocenters on the modern city maps used in the analysis of the activation data for neutrons and TLD data for gamma rays.

The bomb detonated over Nagasaki was a plutonium implosion device that was tested in the first nuclear detonation at Alamogordo, New Mexico in 1945 during the war, and after the war during the Crossroads Able and Baker nuclear tests at Bikini Atoll in 1946. The radiochemical analysis of the nuclear debris and fireball formation measurements of these tests were used to establish the yield of the Nagasaki bomb as 21 ± 2 kt (Malik et al. 1987). The Hiroshima bomb was a gun-type device in which two sub-critical pieces of enriched uranium were propelled together to create the explosion. The Hiroshima bomb was the only one of its design ever detonated. The determination of the yield for the Hiroshima explosion depends on theoretical calculations and measurements of effects of the explosion at Hiroshima. The calculated yield for the Hiroshima device is currently 16 ± 2 kt (Chapter 2).

The DS86 value for the burst height at Hiroshima was 580 ± 15 m (Kerr et al. 1987). The accumulation of extensive sets of neutron activation measurements for thermal and fast neutrons and TLD measurements for gamma rays at Hiroshima have made it possible to use these measurements as an analytic check on the parameters of the explosions, such as the bomb yield and height of burst (HOB). A systematic evaluation of the radiation calculations and measurements for Hiroshima gave the best overall results for a burst height of 600 m with an estimated uncertainty of ±20 m. The thermal neutron and TLD measurements at Nagasaki are too sparse and uncertain near the hypocenter to be used as a test of the Nagasaki explosion parameters. Thus, the DS86 estimate of 503 ± 10 m for the HOB at Nagasaki (Kerr et al. 1987) is still considered to be the best value for that city.

Various values are quoted throughout the literature for the headings of the bombers when the bombs were dropped and for the angles at which the bombs were tilted with respect to the vertical at the time of explosion. The bomber heading and tilt of the bomb is unimportant at Nagasaki because the Nagasaki bomb had a spherical geometry. However, the cylindrical geometry of the Hiroshima bomb created an area of reduced neutron leakage, often referred to as a “blind spot,” through the nose of the device (Kerr and Pace 1988). The bomb tilt and bomber heading must be considered in studies of the fast neutron activation of both sulfur (^{32}P) and copper (^{63}Ni) close to the hypocenter at Hiroshima (Chapter 2). The tilts of the bombs at the times of explosion have been established as 15° ± 3° at Hiroshima and 12° ± 2° at Nagasaki in this reassessment of the explosion parameters at Hiroshima and Nagasaki.

Bomber Headings

Data from the navigator's log for the Hiroshima mission reproduced inside the cover of *Seven Hours to Zero* by Marx (1967) and data from other official reports of the bombing missions have been summarized in reports by Brode (1964), Caudle (1966) and Malik (1985). The data for the Hiroshima and Nagasaki missions from the 1985 report of Malik are provided in Table 1. At Hiroshima, the direction of approach or bomber heading was 265° (or from the east toward the west as illustrated in Figure 1), and at Nagasaki, the bomber heading was 233° (or from the north-east toward the south-west).

Table 1. Bombing mission data (Malik 1985)

Parameter	Hiroshima	Nagasaki
Bomb designation	L-11, Little Boy	F-31, Fat Man
Time of detonation	0815, August 6, 1945	1102, August 9, 1945
Time of fall for bomb	44.4 s	47.0 s
Indicated heading of bomber	262°	233°
Wind speed and direction	8 knots at 170°	1-knot head wind
True heading of bomber	265°	233°
Indicated air speed	200 mph (322 km/h)	200 mph (322 km/h)
True air speed	328 mph (528 km/h)	315 mph (507 km/h)
Indicated altitude	30,200 feet (9.20 km)	28,000 feet (8.53 km)
True altitude of bomber	31,600 feet (9.63 km)	28,900 feet (8.81 km)

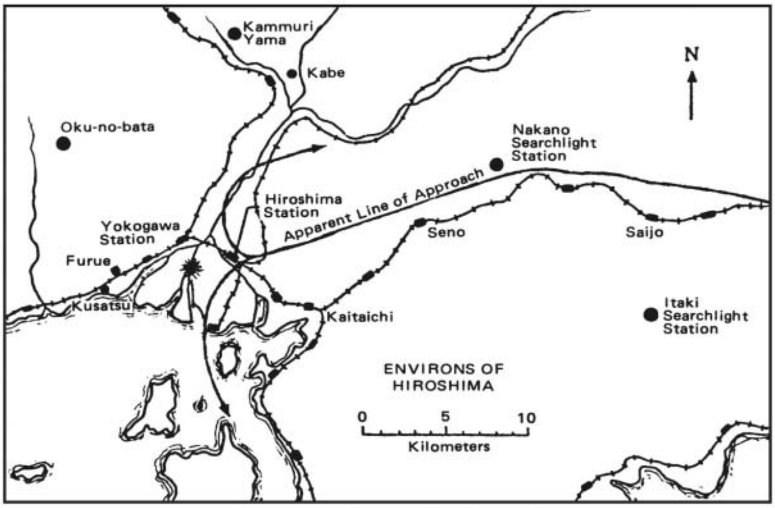

Figure 1. *Map showing environs of Hiroshima and direction of approach of the bombing and observation aircraft (U.S. Strategic Bombing Survey 1947). The bombing aircraft turned to the north after releasing the bomb, and the observation aircraft turned to the south after releasing three parachute-retarded canisters to make pressure versus time measurements.*

Hypocenters

The hypocenter locations in Hiroshima and Nagasaki are defined by a set of east-west (X) and north-south (Y) coordinates on maps of each of the two cities. Maps of the two cities as they existed at the time of the bombings come from the L902 Series of the U.S. Army Map Service. For Hiroshima, however, two maps have been used that have different coordinate systems. Coordinates on the second map were rotated with respect to those on the first map, about a point near the left-hand margin. The first map was used during the 1945 studies by the U.S. Strategic Bombing Survey (USSBS 1947), and the second map was used during later studies by the ABCC and RERF (Kerr et al. 1987). Plate numbers for the U.S. Army maps currently in use at the RERF are 138,499 (June 1946) for Hiroshima and 138,353 (August 1945) for Nagasaki, and the grid units of both maps are 1,000 yards (914 m).

Essentially all of the data on the hypocenters at Hiroshima and Nagasaki were reviewed previously by Hubbell et al. (1969). The estimated locations for the hypocenters were determined by the fall of trees and other vertical objects that toppled in radial directions away from the explosions, the method of triangulation using burn shadows of objects cast by the intense thermal radiation from the fireballs of the explosions, and the measurement of neutron-induced radioactivity in the ground beneath the explosions. Hubbell et al. (1969) were not aware of the complex nature of the neutron activation near the hypocenter at Hiroshima caused by the tilt of the bomb, but they did assign very large uncertainties to the hypocenter locations that were determined from neutron activation of the ground. Thus, the inclusion of these data from the neutron activation studies does not alter their conclusions concerning the location of the hypocenter at Hiroshima.

The review by Hubbell et al. (1969) placed the hypocenter in Hiroshima on the grounds of the Shima Hospital and about 180 meters south of the torii to the Gokoku Shrine (Figure 2). The east-west and north-south coordinates were given as 744.298 and 1261.707, respectively. The review by Hubbell et al. (1969) and a later review by Kerr and Solomon (1976) placed the hypocenter in Nagasaki within a vacant lot used as a tennis court, approximately 90 m east-southeast of the intersection of Route 206 and the road leading to Urakami Cathedral in Matsuyama-cho, and very close to where the Hypocenter Monument is now located in the Peace Park at Nagasaki (CCMDAB 1981). The 1976 study by Kerr and Solomon gave the east-west and north-south coordinates of the hypocenter in Nagasaki as 1293.624 and 1065.936, respectively (Figure 3). It is customary to omit the first two digits of the above map coordinates and to record the hypocenters as X = 93.624 and Y = 65.936 in Nagasaki and X = 44.298 and Y = 61.707 in Hiroshima. The uncertainties in the hypocenter locations for Hiroshima and Nagasaki are estimated at the 99% confidence level to be approximately ±15 m and ±20 m, respectively.

The Japanese government made thorough re-surveys of both Hiroshima and Nagasaki about 25 years ago, and issued new maps on a much larger scale (1:2,500) than the U.S. Army maps (1:12,500), showing far more detail. These newer “Japanese maps” for Hiroshima and Nagasaki are dated 1979 and 1981, respectively. Of course, the maps are of the two cities about 25 years

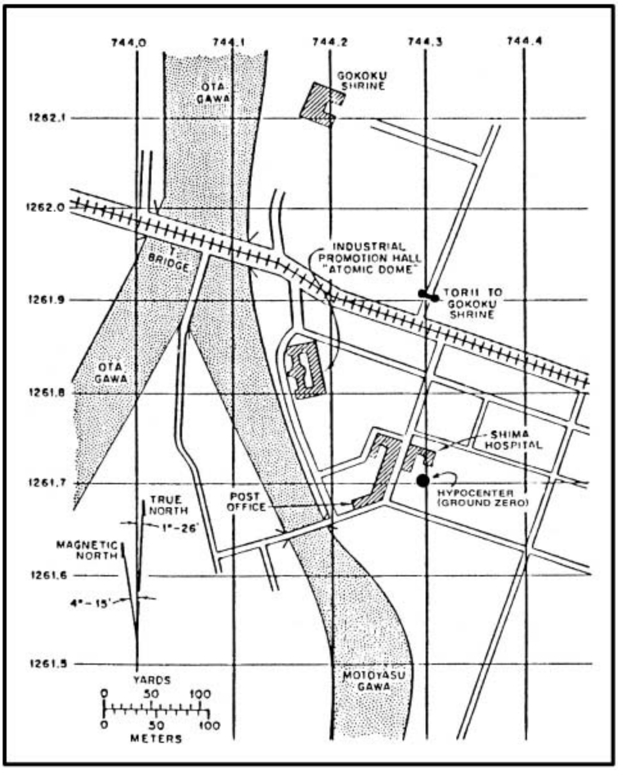

Figure 2. *Hypocenter area on U.S. Army map of Hiroshima.*

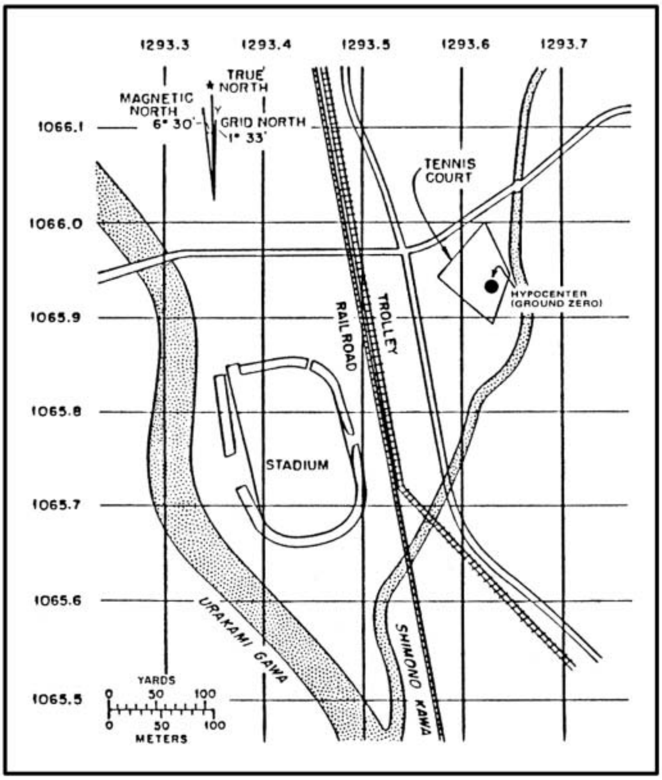

Figure 3. *Hypocenter area on U.S. Army map of Nagasaki.*

ago, and not the two cities at the times of bombings in 1945. The origins of two map systems are also different. The origins of the newer "Japanese maps" are north of the two cities which makes all of the north-south coordinates negative and increasing southward, while the east-west coordinates are positive and increasing eastward. The U.S. Army maps have their origins to the south and west of the two cities so that all coordinates increase northward and eastward. The U.S. Army maps have longitude and latitude markings, but these markings are absent on the newer Japanese maps of the two cities. Thus, it was not a straightforward task to re-locate the hypocenters on the newer Japanese maps (Chapter 5).

The method used was to identify landmarks that had not moved on both the U.S. Army maps and newer Japanese maps, and use these landmarks as control points to re-locate the hypocenters on the new Japanese maps. An effort was made to find control points in as many different directions as possible around the two hypocenters. At Hiroshima, twenty-three control points were identified, and at Nagasaki, nine were identified. These control points consisted of the corners or centers of large buildings and the centers or mid-river points on bridges. There are fewer control points at Nagasaki, due to the geography of the city and the comparative lack of large massive buildings in areas close to the hypocenter. The hypocenters on the newer Japanese maps were selected as those points that best preserved the distances from the control points to hypocenters on the U.S. Army maps for each city.

At Hiroshima, the best east-west and north-south coordinates for the hypocenter on the newer Japanese map were 26.721 and -178.395, respectively, and at Nagasaki, the best east-west and north-south coordinates for the hypocenter on the newer Japanese map were 34.245 and -25.394, respectively. In relation to depicted locations of nearby landmarks such as the Motoyasu Bridge, the hypocenter on the newer Japanese map of Hiroshima is located approximately 15 m to west of the one on the U.S. Army map due to some rather severe distortions affecting the locations of landmarks in the hypocenter area of the U.S. Army map (Chapter 5). At Nagasaki, the hypocenter on the new Japanese map is also located to the west of the one on the U.S. Army map but the difference is only about 3 m. The total uncertainties in the hypocenter locations on the new Japanese maps are assumed to be approximately the same as those for the hypocenter locations on the older U.S. Army maps or ±15 m at Hiroshima and ±20 m at Nagasaki at a 99% confidence level.

The above sets of east-west and north-south coordinates on the U.S. Army maps for Hiroshima and Nagasaki are often designated as the DS86 hypocenters, while the above sets of east-west and north-south coordinates on the Japanese maps for the two cities are often designated as the DS02 hypocenters. This convention is used because slightly different sets of east-west and north-south coordinates on the Japanese maps were used for the Hiroshima and Nagasaki hypocenters in the DS86 studies (Maruyama et al. 1987).

Burst Heights

The burst heights for the detonations have historically been based on two kinds of data: (1) measurements of thermal burn shadows cast by horizontal objects; and (2) the bombardier’s fuse setting for the bombs. The fuse setting was 575 m (1,885 feet) at Hiroshima and 503 m (1,650 feet) at Nagasaki. Many dummy bombs were dropped at Wendover Field in Utah and at places near Tinian Island during the development of the atomic bombs and later over Japan itself during crew training flights, and many of these devices were identical in weight and aerodynamic structure to the actual Hiroshima and Nagasaki bombs, except for the lack of nuclear material. The dummy bombs released smoke at the instant of detonation, and the burst height was observed (at Utah and Tinian) with accurate optical instruments on the ground. Using the data from these drop tests, Brode (1945) estimated the operation altitude of the bomb to be within 15 m (50 feet) of the fusing. These measurements were later compared with the settings of radar fusing devices that were used to detonate the bombs at a specified height above ground (Shelton 1988, p. 1-32). The review of these data by Hubbell et al. (1969) for Hiroshima estimated the burst height to be 580 ± 15 m for that city, and a later review of these data by Kerr and Solomon (1976) for Nagasaki estimated the burst height to be 503 ± 10 m for that city. Despite the confidence in these findings, there are indications that the burst height at Hiroshima could be higher than previously estimated. The presence of large multistory buildings near the hypocenter area of Hiroshima make it impossible to know exactly what triggered the radar altimeters on the bomb. It is possible that the large buildings near the hypocenter area at Hiroshima could have caused the radar altimeters to detonate the bomb at a slightly greater height above ground than planned.

A new burst-height analysis has been made as a part of the DS02 reassessment using the large number of radiation measurements made since DS86 (Chapters 7, 8 and 9). For this analysis, an analytic tool was developed that allowed the radiation transport calculations for neutron and gamma rays at Hiroshima and Nagasaki to be scaled to different burst heights and compared to the radiation measurements for neutrons and gamma rays in the appropriate cities. An example of these comparisons is shown in Figure 4. It was clear from this comparison for ^{60}Co activation, and from other such comparisons in Chapters 7, 8, and 9, that there is a poor match between the measurements and DS86 radiation calculations, not just at the large ground ranges where it is difficult to make reliable measurements, but under the Hiroshima bomb as well, where reliable measurements can be made.

While very low background measurements can address the problems with the neutron activation measurements at long distances from the bomb, it was apparent that the slope of the measurements within approximately 1 km from the bomb could not be matched without a change in the burst height at Hiroshima. Thus, three new sets of radiation transport calculations were made: one at the DS86 burst height of 580 m, a second at a burst height of 610 m, and a third at 600 m. These transport calculations were then used to determine the “goodness” of fit between the measured and calculated values at each of the calculated HOBs. Other burst heights for which a full set of transport calculations did not exist were scaled for analytic evaluation. A systematic evaluation of the fits between the calculated and measured values over a range of burst heights produced the best agreement at 600 m. As can be seen in the ^{60}Co example contained in Figure 4, the measurements are in much better agreement with the calculation done at 16-kt yield and 600-m HOB than was obtained with DS86, which was calculated at a 580-m HOB and a 15-kt yield. Overall the best agreement with the measurements was obtained from the calculations for a yield of 16 kt and 600-m HOB. For a 16-kt yield, the total measured-to-calculated ratio (M/C) using all

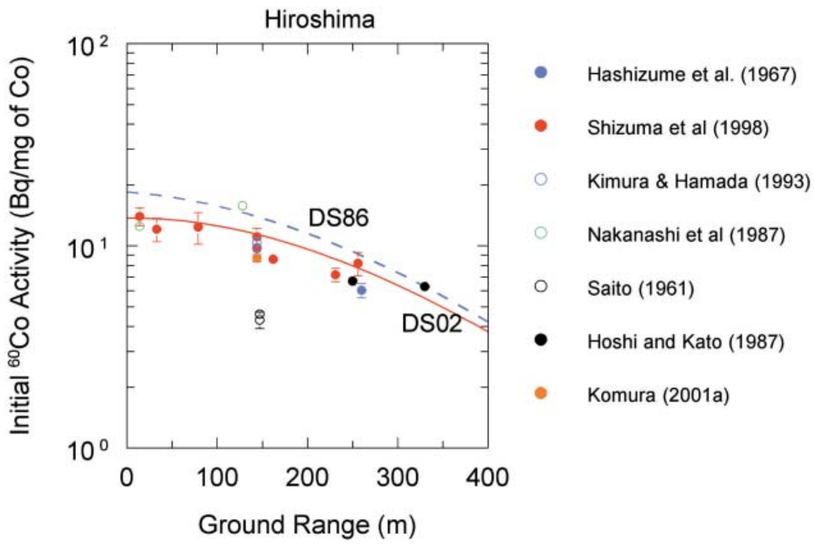

Figure 4. *Comparison of ^{60}Co measurements at Hiroshima with DS86 and DS02 calculations at close-in ground ranges of 400 m or less. The DS86 calculations are for a 580-m burst height and 15-kt yield at Hiroshima, and the DS02 calculations are for a 600-m burst height and 16-kt yield. The references for the measurements shown in the figure can be found in Chapter 8, Part A.*

neutron activation and TLD measurement points was 0.86 at a 580-m HOB and 1.07 at a 610-m HOB, whereas the total M/C was 0.99 at a 600-m HOB. The total M/C using all neutron activation and TLD measurement points was 0.88, with a 55% higher standard deviation, at the 580-m HOB and 15-kt yield used in DS86.

The above results prompted a closer look at the burst height data from thermal-shadow studies by Kimura and Tajima (1953) and Nagaoka and Arakawa (1959). These two studies are cited by both Hubbell et al. (1969) and the Japanese Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki (CCMDAB 1981). The thermal-shadow studies of Kazuharu Kimura and Eizo Tajima were made in 1945 immediately after the bombings, but the results were not published until 1953 (Kimura and Tajima 1953). Their original data for estimating the burst height at Hiroshima were reanalyzed by Hubbell et al. (1969) and the burst heights at Hiroshima as determined in their reanalysis of the original data of Kimrua and Tajima (1953) are shown in Figure 5. For the burst height at Hiroshima, Kimura and Tajima gave 577 ± 20 m, from calculations using eight thermal shadows cast on wood surfaces at ground ranges of 500 m or more (Hubbell et al. 1969). Kimura and Tajima also made seven measurements on granite at ground ranges of less than 500 m and one measurement on a painted wall surface at the Postal Savings Bureau at a ground range of approximately 1,600 m (Figure 5). These measurements were considered to be less reliable and were not included in the 577-m average value published by Kimura and Tajima (1953). The same thermal shadow at the Postal Savings Bureau was also measured by William Penney and a team from the Manhattan Project (Penney et al. 1970), and the results of their measurements at the Postal Savings Bureau were essentially the same of those of Kimura and Tajima (Hubbell et al. 1969). The thermal shadow measurements at the Postal Savings Bureau by two independent teams gave a burst height value that was essentially the same as the currently recommended DS02 value of 600 m for the burst height at Hiroshima.

As shown in Figure 5, the overall trend in the data of Kimura and Tajima (1953) is toward smaller estimated burst heights at smaller ground ranges due to the fact that the burst height based on the seven granite measurements at ground ranges of less than 500 m was only 546 m (Hubbell et al. 1969). The thermal burn shadows resulting from the exfoliation of granite are not as sharply defined as those on wooden surfaces, and there is more scatter in the burst height estimates based on the individual thermal shadows on granite surfaces (Figure 5). The study by Arakawa and Nagaoka (1959) made use of the extensive thermal shadow measurements of Shogo Nagaoka. These data came from measurements of shadows, mostly on granite, and included 1,172 measurements of shadows indicating the elevation of the explosion or burst height at 37 different sites, mostly graveyards, at Hiroshima. The distribution of the estimated burst heights from the individual shadow measurements by Nagaoka and the average of 606 ± 74 m for this distribution are shown in Figure 6 (Arakawa and Nagaoka 1959). Thus, the burst height data from two of the better studies of thermal shadows at Hiroshima tend to support our recommended DS02 value of 600 m for the HOB at Hiroshima. Nevertheless, the large scatter in the burst height estimates from the many different studies reviewed by Hubbell et al. (1969) caused them to place more credibility in the fuse settings for the bombs. As noted previously, the large buildings near the hypocenter at Hiroshima may have caused the radar altimeters to detonate the bombs at a slightly higher altitude than expected, and more credibility is placed here on the fact that the best overall match between radiation calculations and measurements for thermal neutrons, fast neutrons, and gamma rays was obtained for a 600-m HOB at Hiroshima.

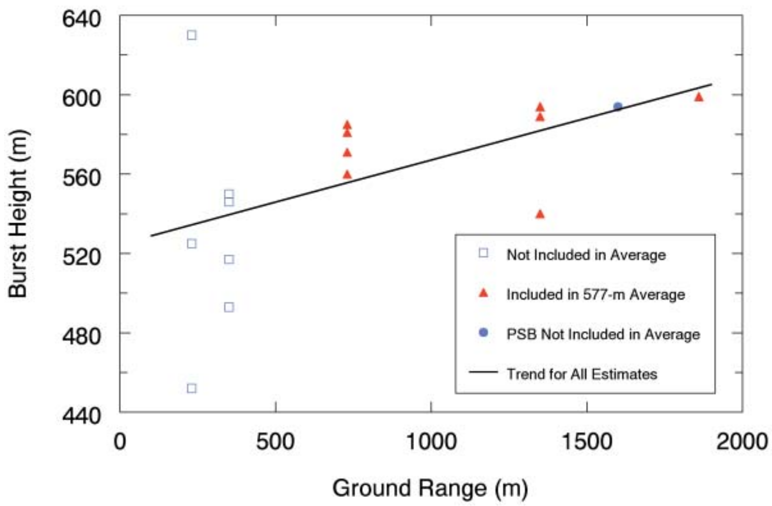

Figure 5. *Plot of individual burst-height estimates at Hiroshima from thermal shadow measurements by Kimura and Tajima (1953). They gave a burst height at Hiroshima of 577 m based on eight measurements on wood surfaces (red triangles). Not included in their average value of 577 m were the burst heights determined from seven thermal shadow measurements on granite surfaces at ground ranges of less than 500 m (open blue squares) and one thermal shadow measurement on a painted wall surface at the Postal Savings Bureau (PSB) at a ground range of approximately 1,600 m (Hubbell et al. 1969).*

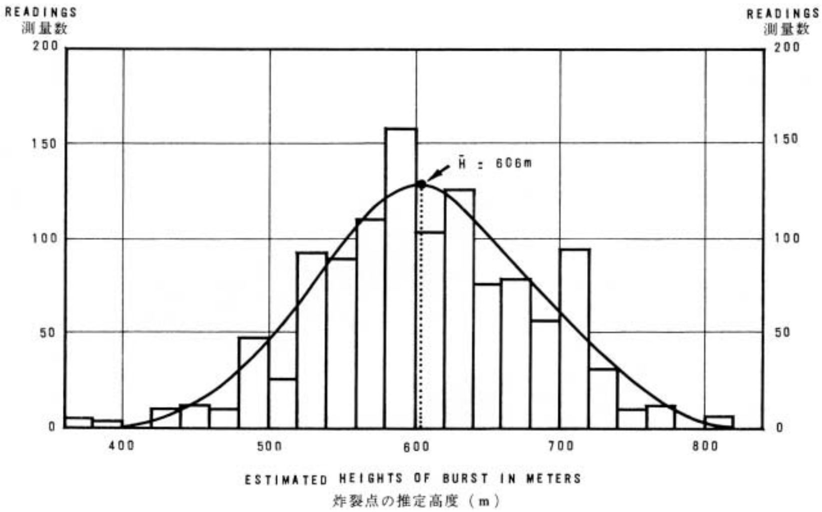

Figure 6. *Plot showing the distribution of individual burst-height estimates at Hiroshima from thermal shadow measurements on 1,172 stone surfaces at 37 sites by Nagaoka (Arakawa and Nagaoka 1959). The mean of the distribution is 606 m and the standard deviation of the mean is 74 m.*

At Nagasaki, it was difficult to find neutron activation samples and TLD samples within approximately 500 m of the hypocenter because of the nearly total devastation of all buildings and other structures within this area, and the available thermal neutron measurements and TLD measurements are too sparse and uncertain near the hypocenter to use them as a test of the explosion parameters. Thus, the DS86 HOB value of 503 m (Kerr et al. 1987) is still considered to be the best value at Nagasaki, and the estimated uncertainties in the HOBs for the two cities are ±10 m for Nagasaki and ±20 m for Hiroshima at a 99% confidence level.

Bomb Yields

Original plans were to use two different methods to measure the yields of the Hiroshima and Nagasaki bombs: (1) rate of growth of the fireball which forms after the bomb explodes; and (2) measurement of the air pressure versus time after the explosion. The first method was to have used a camera in an aircraft accompanying the bomber to obtain photographs of the early fireball expansion as a function of time. This technique had been used during the Trinity test at Alamogordo, New Mexico with excellent results (Malik et al. 1987). Unfortunately, the films made at Hiroshima were accidentally destroyed during development, and no films were made at Nagasaki because the aircraft carrying the special camera failed to arrive as planned. The second method was to determine the blast overpressures by using instruments dropped from a second accompanying aircraft with the data telemetered back to the aircraft. One successful “pressure versus time” measurement was made at Hiroshima, but the only successful measurement at Nagasaki went off-scale and could be interpreted only partially (Malik 1985). Thus, the methods used to establish the bomb yields at Hiroshima and Nagasaki are determined by other available data, which are quite different.

Nagasaki

Radiochemical analysis of the debris of a nuclear explosion has been a widely used technique for yield determination, but no debris samples were collected for the bombs dropped in Japan. However, data are available from debris sampling of clouds from exact duplicates of the Nagasaki bomb that were tested at Trinity and at the Crossroads Able and Baker nuclear tests. These data, reevaluated by modern methods, are provided in Table 2 (Malik et al. 1987). The mean of the three values is 20.8 kt with an overall uncertainty of about ±10%. Crossroads Able, an airdrop over naval targets, supplied some fireball records in addition to those from Trinity. However, a large bombing error at Crossroads Able put the fireball outside the field of view of all but one camera. The yield derived from that one set of records agrees well with that derived from the radiochemical method. The two fireball records are listed in Table 2. Their mean is 21.1 kt, which agrees closely with the radiochemical determinations, and the estimated yield based on both the radiochemical and fireball formation data is 21 kt with an overall uncertainty of approximately ±2 kt (Malik et al. 1987).

Similarly, a 21-kt yield estimate is supported for the Nagasaki bomb by the blast damage studies of Penny et al. (1970) and the theoretical calculations carried out at LANL for this reassessment (Chapter 2). These recent LANL calculations for the Nagasaki bomb produced a yield of 21.4 kt within a tight range from 18 to 22 kt. The blast damage studies by Penny et al. (1970) are considered to be very important, since they provide the only estimates of yield based

Table 2. Yield estimates for the Nagasaki bomb

Method	Yield (kt)
Radiochemistry	
Trinity test	20.3[a]
Crossroads Able test	20.4[a]
Crossroads Baker test	21.7[a]
Fireball formation	
Trinity test	20.8[a]
Crossroads Able test	21.4[a]
Theoretical yield calculations	21.4[b]
Recommended yield	21 ± 2[c]

[a]See Table 1 of Chapter 1 in the DS86 Final Report (Malik et al. 1987).
[b]See Chapter 2.
[c]See text for a discussion of the uncertainties.

on direct studies of the Nagasaki explosion. From field observations of blast damage at Nagasaki and from laboratory measurements of the effects of pressure and drag on various objects, Penny and his colleagues estimated the yield of the Nagasaki bomb to be slightly more that 20 kt. Thus, the bomb yield at Nagasaki is considered to be well established as 21 kt with an overall uncertainty limit of approximately ±2 kt. For estimating propagation of errors, it is believed that this limit can be taken to represent about 2.5 standard deviations (Malik et al. 1987).

Hiroshima

The DS02 value for the yield of the Hiroshima bomb is based on the LANL calculations that were done for this reassessment (Chapter 2). Theoretical calculations with modern weapon-design codes can produce reliable estimates of yield, but the accuracy depends to some extent on the design of the bomb. For the Nagasaki bomb, there are no significant areas of uncertainty (Malik et al. 1987). There is a large uncertainty in the calculations for the Hiroshima bomb that is attributable to not knowing the exact configuration of the core at the time neutron multiplication began. If it is assumed the bomb detonated exactly as planned, then the calculated DS02 yield is 16.1 kt. Calculations for other highly probable core configurations at the time of detonation gave yield estimates ranging from a low of 15 kt to a high of 18 kt. To the nearest kiloton, the currently calculated yield of 16 kt, with an overall uncertainty of about ±2 kt, is considered to be the most technically defensible estimate of the bomb yield at Hiroshima. For estimating propagation of errors, it is believed that this limit can be taken to represent 2.5 standard deviations. A range of bomb yields between 14 kt and 18 kt at a 99% confidence limit is supported by data from a variety of other Hiroshima studies.

The DS86 yield for the Hiroshima bomb was estimated from a weighted average of seven “absolute” and “relative” methods of yield determination, combined with theoretical calculations of the yield (Malik et al. 1987). The weighted average of 15.25 kt, after round-off to 15 kt, was adopted as the Hiroshima yield (Table 3). During this reassessment, the absolute and relative methods for establishing the DS86 yield at Hiroshima have been reevaluated. For example, new

Table 3. Supporting data for the recommended DS02 Hiroshima yield of 16 ± 2 kt on theoretical calculations by the Los Alamos National Laboratory

Method	DS86 Value (kt)	DS02 Revision (kt)
Absolute methods		
TLD measurements of gamma rays	18 (3)[a]	17[b]
Pressure versus time measurements	16 (3)[a]	17[c]
Charring of Cypress	15 (2)[a]	16[d]
Sulfur (P^{32}) activation by fast neutrons	13 (1)[a]	18[e]
Copper (Ni^{63}) activation by fast neutrons	NA[f]	15[f]
Blast wave damage	12 (1)[a]	13[g]
Critical separation experiment	NA[h]	16[i]
Relative methods		
Comparison of blast effects at both cities	15 (1)[a]	15[j]
Comparison of thermal effects at both cities	14 (3)[a]	14[k]
Theoretical yield calculations	15 (2)[a]	16[l]
Recommended yield	15 ± 3[a]	16 ± 2[l,m]

[a]See Table 4 of Chapter 1 in the DS86 Final Report (Malik et al. 1987). The DS86 yield was calculated as a weighted mean of the various yield estimates in Table 3, using the weighting factors in the parentheses.

[b]Based on data in Table 12 in Chapter 7, Part B.

[c]DS86 value based on a burst height of 580 m was 16.3 kt or 16 kt when rounded, and the DS02 value based on a burst height of 600 m is 16.7 kt or 17 kt when rounded. The revised value of 16.7 kt for a 600-m burst height was provided by Kennedy (2002).

[d]DS86 value was based on charring of cypress on the roof of the Chugoku Electric Company at a slant range of 877 m from the explosion (burst height = 580 m, ground range = 676 m, cypress elevation = 21 m). The newer DS02 value is based on a slant range of 900 m (burst height = 600 m, ground range = 690 m, cypress elevation = 21 m). The newer DS02 value was obtained using the square of the ratio of the slant ranges or $(900\ m/877\ m)^2$ times the DS86 value of 15 kt to get 15.8 kt or 16 kt when rounded.

[e]See Table 9 in Chapter 9, Part A.

[f]Based on data in Table 7 in Chapter 9, Part B. These data were not available for use in the estimation of bomb yield during the DS86 studies.

[g]Reevaluated using more recent data from 2D blast-code calculations (Samuels 1987).

[h]Not used in the DS86 estimation of the Hiroshima bomb yield.

[i]See Chapter 2.

[j]See Table 4 and Equations (2) and (3) of Chapter 1 in the DS86 Final Report (Malik et al. 1987). If the blast effects are scaled using ground ranges for equal effects at both cities and a 21-kt yield at Nagasaki, Equation (2) yields the same 14.3-kt value for both DS86 and DS02, and if the blast effects are scaled using slant ranges, Equation (3) gives a DS86 value of 14.9 kt and a DS02 value of 15.0 kt. Thus, the DS86 and DS02 values for the Hiroshima bomb yield based on distances for equal blast effects remain essentially the same when rounded.

[k]See Table 4 and Equation (1) of Chapter 1 in the DS86 Final Report (Malik et al. 1987). If the thermal effects are scaled using slant ranges and a 21-kt yield at Nagasaki, Equation (1) gives DS86 and DS02 values that are essentially the same when rounded.

[l]An average value is not used as the basis for the DS02 value for the Hiroshima bomb yield. The theoretical yield of 16.1 kt when rounded to 16 kt was selected as the most technically defensible estimate for the Hiroshima bomb.

[m]See text for a discussion of the uncertainities.

TLD measurements have been made (Chapter 7, Part A), the existing TLD measurements have been corrected for distance from the hypocenter, and all TLD measurements have been reevaluated (Chapter 7, Part B). The 1945 measurements of sulfur (^{32}P) activation by fast neutrons have been corrected for location errors and reevaluated (Chapter 9, Part A), and new measurements of copper (^{63}Ni) activation by fast neutrons have been made (Chapter 9, Part B). The TLD and fast neutron activation (^{32}P and ^{63}Ni) data are considered to be very important because they are the measurements most directly related to survivor dose in estimating the Hiroshima yield.

The relative methods for estimation of the Hiroshima bomb yield rely on observed ground ranges for equivalent blast and thermal effects at the two cities, scaled to a yield of 21 kt at Nagasaki (Malik et al. 1987). These relative yield values have not changed since DS86 (Table 3). The absolute methods address the yield of the Hiroshima bomb directly (Malik et al. 1987). These indices of yield include the “pressure versus time” measurements for the Hiroshima explosion (Kennedy at al. 1984), blast damage at Hiroshima (Penny et al. 1970), charring of cypress on the roof of the Chugoku Electric Company (Tajima 1984), TLD measurements (Chapter 7), fast neutron activation (Chapter 9), and a critical separation experiment conducted during DS86 using a replica of the Hiroshima bomb (Whalen 1987). The reevaluation of the critical separation experiment during this reassessment effort is discussed in Chapter 2. With the exception of the TLD measurements, all of the yield estimates obtained by the absolute methods have increased by one kiloton or more compared to the DS86 yield estimates (Table 3). The DS86 yield estimate for Hiroshima based on the TLD measurements was found to decrease by one kiloton bringing it into better agreement with the DS02 recommended yield of 16 kt based on the theoretical calculations by LANL.

For comparison with DS86, the yield estimates were calculated for the reevaluated sulfur activation and TLD measurements and for the new copper activation measurements using Beers’ equations for a weighted mean (Beers 1957; Kerr and Solomon 1976). In the sulfur-activation calculations, each measured value (M) for sulfur activation and its standard deviation (σ) were divided by the calculated value (C) for a titled bomb (Table 8 of Chapter 9, Part A) and multiplied by the energy yield of 16 kt used in the DS02 calculations for Hiroshima (Table 9 of Chapter 9, Part A). The energy yield was then calculated as a weighted mean in which the reciprocals of the square of the standard deviations of the yield estimates for each of the sulfur activation measurements were used as the weighting factors (Beers 1957; Kerr and Solomon 1976). As shown in Table 3, this calculation produced a yield estimate of 18 kt (±2 kt) for the sulfur (^{32}P) activation measurements (Chapter 9, Part A), an estimate of 15 kt (±2 kt) for the ^{63}Ni activation measurements (from Table 7 of Chapter 9, Part B), and an estimate of 17 kt (±3 kt) for the TLD measurements (from Table 12 of Chapter 7, Part B).

Collectively, the current absolute methods of yield determination clearly indicate a value slightly greater than the DS86 yield estimate of 15 ± 3 kt and tend to support the recommended DS02 yield of 16 ± 2 kt for the Hiroshima bomb.

Tilt of Bombs at Time of Explosion

Assessments of the energy yield of Hiroshima and Nagasaki bombs from pressure versus time measurements by Brode (1964) and Malik (1985) provide data on the tilt of the bombs at the time of explosion. These assessments require detailed data on the bomb trajectories, and the bomb trajectories are quite complicated because the bombs were falling through air, which is a resisting medium. Experiments show that for low velocities the resistive force is proportional to the velocity of a falling object, and for higher velocities, it is more nearly proportional to the square of the velocity (Page 1952). As the velocity is increased, the power of velocity to which the resistance is proportional rises further, becoming as great as 5 when the velocity of the speed of sound is reached. Thereafter, the power falls, becoming approximately 1.6 at extremely high velocities. It has typically been assumed that the resistive force (or drag force) of the air on the bombs was approximately equal to the square of the velocity, since this condition applied over most of the bomb's trajectory. The trajectory calculations of Brode (1964) and Malik (1985) use slightly different burst heights than are being used in DS02, but these differences are not significant in the estimation of the tilts of the bombs at the time of explosion.

Malik (1985) calculated the trajectory of the Hiroshima and Nagasaki bombs during his investigations of the bomb yields from the pressure records of the explosions. He used drop test data from Muroc Dry Lake near Edwards Air Force Base in southern California (Site M) and projectile calculations assuming the projectile drag was proportional to the square of its velocity (v. Karman and Biot 1940). Because drop test data for the Hiroshima device could not be located, the test data from a Thin Man bomb (an earlier, longer gun device with cross-sectional area and weight similar to the Hiroshima bomb) was used (Appendix A). The time of fall of the Hiroshima bomb was based on the test data at Muroc plus trajectory calculations for other altitudes using the test data to derive a drag coefficient for the resistive forces of the air. The angle-of-impact data from the drop tests suggest the tilt of the bombs at the time of explosion was about 12° at Hiroshima and 10° at Nagasaki (Appendix A), whereas Malik's trajectory calculations suggest the tilt of the bombs at the time of explosion was 17° at Hiroshima and 12.2° at Nagasaki.

Brode (1964) also made trajectory calculations for the Hiroshima bomb assuming the projectile drag was proportional to the square of the velocity. Figure 7 shows the final horizontal and vertical velocities and the drop times calculated for the Hiroshima bomb using a wide range of drag coefficients. Brode did not calculate the tilt of the bomb, but it can be obtained since the final horizontal velocity divided by the final vertical velocity is equal to the tangent of the tilt angle at the time of explosion. For the 44.4-s drop time at Hiroshima (Table 1), the tilt angle is equal to the arc tan [(407 feet/s)/(1,282 feet/s)] or 17.6° (Figure 7). The drop parameters used by Brode (1964) were specific to the Hiroshima bomb, but they are close enough to the Nagasaki drop parameters that we can also use the results to make an approximate estimate of the bomb tilt at Nagasaki. For the 47.0-s drop time at Nagasaki (Table 1), the tilt angle is equal to the arc tan [(265 feet/s)/(1,145 feet/s)] or 13° (Figure 7).

Based on the Muroc drop test data (Appendix A) and the results of calculations by both Malik (1985) and Brode (1964), the tilt angle of the bombs at the time of explosion was estimated to be 15° at Hiroshima and 12° at Nagasaki with an uncertainty at a 99% confidence interval of ±3° at Hiroshima and ±2° at Nagasaki. As mentioned earlier, the tilt of the bomb is unimportant at Nagasaki because the Nagasaki bomb was a spherical implosion-type device. However, the Hiroshima bomb was a cylindrical gun-type device with a blind spot in the neutron leakage through both the nose and tail of the device. The blind spot in the neutron leakage through the nose of the Hiroshima device affects the fast neutron activation of sulfur (^{32}P) close to the hypocenter in a very complicated manner (Kerr and Pace 1988), and the bomb tilt and bomber heading must be considered in studies of the fast neutron activation of both sulfur (^{32}P) and copper (^{63}Ni) close to the hypocenter at Hiroshima (Chapter 2).

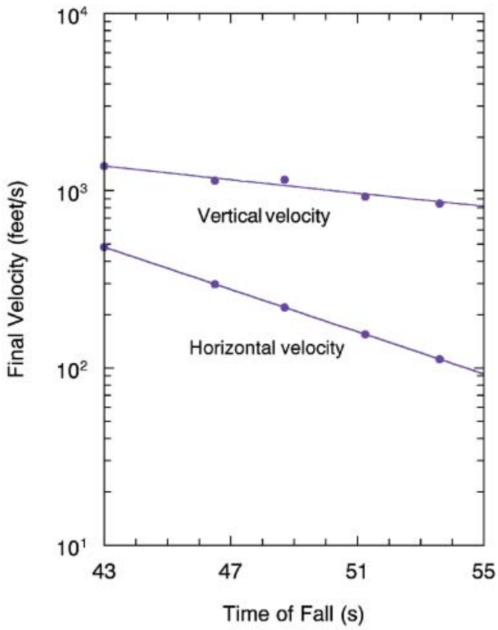

Figure 7. *Final velocities for a free-falling projectile in air having an initial horizontal velocity of 481 feet/s (328 miles/h or 528 m/h) and falling 29,610 feet (9.0 km) as a function of time of fall (s) for a projectile subjected to a resistive force of different magnitudes (Brode 1964). The 43-s fall time is that for a free-falling projectile in a non-resistive medium (or vacuum).*

Conclusions and Discussion

The current reassessment maintains the explosion parameters used in DS86 for Nagasaki, while refining the bomb yield and burst height for the Hiroshima bomb and the hypocenter location of the Hiroshima detonation on the newer 1979 Japanese map of Hiroshima. The recommended DS02 values for the calculations of the air transport radiation fields and ultimate survivor doses from the Hiroshima and Nagasaki detonations are summarized in Table 4. For propagation of errors in the radiation transport calculations and survivor dose estimates, the uncertainties attached to the energy yields can be taken to represent 2.5 standard deviations. The uncertainties attached to all other values can be taken to represent 3.0 standard deviations.

The bomber heading at Nagasaki and the tilt of the bomb at time of explosion are given for completeness and are unimportant because the Nagasaki bomb had a spherical geometry. However, the Hiroshima bomb had a cylindrical geometry, and there was a "blind spot" in the neutron leakage through both the nose and tail of the device. The blind spot in the neutron leakage through the nose of the Hiroshima device affects the fast neutron activation close to the hypocenter in a very complex manner, and the bomber heading and bomb tilt at the time of explosion are important parameters for the radiation transport calculations at ground ranges of 1,000 m or less at Hiroshima.

An equation that can be used to accurately calculate the effect of bomb tilt at Hiroshima on copper (^{63}Ni) activation and sulfur (^{32}P) activation by fast neutrons at ground ranges of 1,000 m or less was developed as part of this reassessment effort and is provided in Chapter 2. The effect of bomb tilt on comparisons between the radiation calculations and measurements for fast neutrons at Hiroshima can also be found in Chapter 9.

Table 4. Recommended DS02 parameters for radiation transport calculations at Hiroshima and Nagasaki[a]

Parameter	Hiroshima	Nagasaki
Bomber heading	265°	233°
Hypocenter - U.S. Army map[b]		
East-west coordinate	744.298	1293.624
North-south coordinate	1261.707	1065.936
Estimated uncertainty	±15 m	±20 m
Hypocenter - Japanese map[c]		
East-west coordinate	26.721	34.245
North-south coordinate	-178.395	-25.394
Estimated uncertainty	±15 m	±20 m
Burst height	600 ± 20 m	503 ± 10 m
Energy yield	16 ± 2 kt	21 ± 2 kt
Bomb tilt at time of explosion	15° ± 3°	12° ± 2°

[a]For propagation of errors in the radiation transport calculations and survivor dose estimates, the uncertainties attached to values for the energy yields can be taken to represent 2.5 standard deviations and the uncertainties attached to all other values can be taken to represent 3.0 standard deviations.

[b]These sets of east-west and north-south coordinates on the U.S. Army maps are often referred to throughout this report as the DS86 hypocenters at Hiroshima and Nagasaki.

[c]These sets of east-west and north-south coordinates on the Japanese maps are often referred to throughout this report as the DS02 hypocenters at the two cities because slightly different sets of east-west and north-south coordinates on the Japanese maps were used for the hypocenters at Hiroshima and Nagasaki in the DS86 Final Report (Maruyama et al. 1987).

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Appendix A

The drop test data in Table A-1 are taken from Malik (1985). These data were obtained during drop tests of dummy bombs at Muroc Dry Lake near Edwards Air Force Base in southern California or so-called Site M. Because drop test data for the Hiroshima bomb at other sites could not be located, the data for a Thin Man bomb, an earlier somewhat longer gun device with cross-sectional area and weight similar to Little Boy, was used by Malik (1985). These data are designated as M-27 in Table A-1. The drop test data designated as M-31 in Table A-1 were used by Malik (1985) for the Fat Man device dropped at Nagasaki.

TABLE A-1

SUMMARY OF SITE M TEST DATA

Serial No. of Test	Type & Serial	Date of Test	Description	Altitude (ft)	True Air Speed (mph)	Standard Ground Speed (mph)	Measured Range (ft)	Effect of D.B.W. (ft)	Earth Rotation & Rack Lag (ft)	Standard Range (ft)	Vacuum Time (s)	Time Lag (s)	Standard T_f (s)	Vert. Comp. Strike Velocity (ft/s)	Angle of Yaw (deg)	Diff. Ball. Range Wind (mph)	Angle of Impact (deg)	C_x	C_t
M-13	Thin	3-06-44	Standard Thin Man	19300	280	228	11300	- 63	22	11260	34.65	0.65	35.30	----	----	19	----	6.55	8.43
M-15	Fat	3-14-44	Standard Round Tail	19300	278	196	8720	-139	32	8549	34.65	2.92	37.57	785	15.5	20	9.	1.64	1.30
M-16	Fat	3-14-44	Standard Round Tail	19300	278	206	-----	----	--	-----	34.65	3.37	38.02	766	19.	--	10.	----	1.10
M-20	Thin"M"	6-14-44	Test of Flanged Lug	27700	300	230	13210	- 45	44	13209	41.73	0.83	42.56	1361	0.	52	14.	4.95	9.58
M-21	Fat #5	6-15-44	Standard Box Tail	28075	300	192	9415	-397	42	9060	41.79	5.26	47.05	859	9.	26	6.	1.23	1.08 (3)
M-22	Fat #13	6-16-44	Standard Box Tail	-----	---	---	-----	----	--	-----	41.73	5.72	47.45	859	9.5	--	5.	----	---- (3)
M-23	Fat #15	6-17-44	Standard Box Tail	28050	300	238	12685	-424	42	12300	41.77	6.03	47.80	792	14.	22	8.5	1.48	1.02 (3)
M-24	Fat #8	6-19-44	External Drag Fins	28000	300	215	8985	-708	34	8310	41.73	8.85	50.58	797	2.	30	3.	0.64	0.64 (2)
M-25	Fat #11	6-20-44	Internal Parachute Tail	27960	300	206	9930	-317	30	9640	41.70	5.76	47.46	891	1.	13	8.25	1.35	1.07 (1)
M-26	Thin"O"	6-21-44	75° C.G.	27975	300	184	10590	-163	41	10470	41.72	1.37	43.09	1149	0.	39	10.	5.29	5.77
M-27	Thin"H"	6-21-44	77° C.G.	28065	315	220	13005	-101	41	12945	41.78	1.33	43.11	1136	0.	24	12.	7.90	5.95
M-28	Fat #7	6-23-44	Lengthened Box Tail	28070	300	230	12290	-385	34	11940	41.79	6.01	47.80	779	18.	23	9.	1.46	0.96
M-29	Fat #9	6-24-44	External Drag Fins	27930	300	242	12340	-683	37	11695	41.68	9.74	51.42	779	3.5	27	8.	0.90	0.55 (2)
M-30	Fat #12	6-27-44	Internal Parachute Tail	28010	300	260	13995	-443	42	13590	41.73	5.71	47.44	897	1.5	17	8.5	1.27	1.01 (1)
M-31	Fat #6	6-27-44	Internal Parachute Tail	28025	300	260	13700	-425	42	13315	41.75	5.95	47.70	901	2.	18	10.	1.12	1.01 (1)

(1) Similar Units with Internal Drag Fins
(2) Similar Units with External Drag Fins
(3) Similar Units with Standard Box Tail