Chapter 1

YIELDS OF THE BOMBS

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The calculations reported in later chapters require knowing how many fissions took place in each bomb. The literature gives the average energy released per fission; so an equivalent quantity is the energy released by each bomb. The energy released is called the "yield". The yield is given in kilotons. Here "kiloton" is used as a unit of energy, not of mass. It is defined[1] as 10^{12} calories or approximately the energy released in the explosion of one kiloton (kt) of TNT.

The bomb exploded over Hiroshima was a gun-type device using enriched uranium and was the only detonation ever made of this type of device. The bomb exploded over Nagasaki was an implosion device using plutonium and was the same type as the bombs tested at Trinity in New Mexico and at the Able and Baker tests of Operation Crossroads at Bikini Atoll in 1946. These test data were the primary source of information used in determining the yield of the Nagasaki bomb. The yield of the Hiroshima bomb was determined by comparison with effects observed in the two cities and by some of the other methods listed below.

Because of the importance of the yields to the reassessment program, they have been studied many times.[2–4] Yield estimates can be made from:

Theoretical calculations	Thermal radiation	Blast wave observations
Radiochemistry	Gamma-ray measurements	Overpressure versus time
Fireball radius versus time	Neutron measurements	Effects upon objects

THEORETICAL CALCULATIONS

Calculations with modern weapon-design computer codes can produce reliable estimates of yield. The effort required and the accuracy achieved depend on the design of the bomb. For the Nagasaki bomb, calculations give 22 kt, and the people who made the calculations feel there are no significant areas of uncertainty in the theory. Modern calculations for the Hiroshima bomb are more difficult; the calculated values give a range of yields with a most probable yield of 15 kt. Because the bomb was a gun assembled device, uncertainties in the degree of assembly and the start of the detonation introduce considerable uncertainty in the yield calculations.

MEASUREMENTS AT THE TIME OF THE BOMBING

The plans were to use two different methods to measure the yields of the Hiroshima and Nagasaki explosions; rate of growth of the fireball and free-in-air overpressure versus time. 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 tried at the Trinity test with excellent results. Unfortunately, the films made at Hiroshima were accidentally destroyed, and no films were made at Nagasaki because the aircraft did not arrive on station.

The other planned method of yield measurement was to determine the blast overpressure by using instruments dropped from an accompanying aircraft with the data telemetered back to that aircraft. One successful measurement was made at Hiroshima (discussed below); a measurement at Nagasaki went off-scale and could be interpreted only partially.

YIELD OF THE NAGASAKI BOMB

Radiochemical analysis of the debris of a nuclear explosion is the accepted technique for yield determination. No debris samples were collected, however, for the bombs dropped in Japan. Cloud sampling yielded data for the Nagasaki-type bombs tested at Trinity and at both Crossroads tests. These data, reevaluated by modern analysis methods, are given in Table 1. The mean of the three values is 20.8 kt and radiochemical analysis gives an outside uncertainty limit of 10%.

Crossroads Able, an airdrop of a Nagasaki-type bomb over naval targets, supplied some fireball records for that device in addition to those from Trinity; but the large bombing error put the fireball outside the field of view of all but one camera. The yield derived from that one record agreed well with that derived by the radiochemical method. The two fireball values are listed in Table 1. Their mean is 21.1 kt, which agrees with the mean of the radiochemical determinations.

Another estimate of the yield at Nagasaki is available from the work of Penney et al[5] on the pressure and drag damage on objects due to the shock wave. They calibrated their measurements with questionable scale model studies (see discussion below). They estimated the yield at Nagasaki to be 22 kt with the equivalent of a standard deviation of 2 kt or 10%. Their estimate is consistent with the radiochemical and fireball data but with higher

Table 1. The Best Yield Estimates for the Nagasaki Bomb (for a discussion of uncertainties, see text).

Method	Yield
Radiochemistry	
Trinity test	20.3 kt
Crossroads Able test	20.4
Crossroads Baker test	21.7
Fireball	
Trinity test	20.8
Crossroads Able test	21.4
Theoretical calculations	22
Recommended yield	21

uncertainty and with unknown bias.

One more estimate is available from comparison of calculated and measured doses to roof tiles in which thermoluminescence could be measured. These measurements are discussed in more detail below. The conclusion was that the yield for Nagasaki was about 19 kt but with much higher uncertainty.

The best yield data for Nagasaki are summarized in Table 1. The yields estimated by the two best methods (radiochemistry and fireball measurements) are in agreement, therefore, 21 kt was taken as the yield for the Nagasaki bomb with 10% uncertainty.

YIELD OF THE HIROSHIMA BOMB

As already noted, no tests of the Hiroshima-type bomb were made. The yield was determined by both absolute and relative methods (i.e., relative to the Nagasaki explosion). The absolute method included theoretical calculations, pressure versus time measurements, blast wave damage, charring of cypress, gamma-ray measurements, and neutron measurements. The relative methods were for blast and thermal effects.

Pressure versus Time Measurements

The shock overpressure versus time measurement used gages in parachute-retarded canisters dropped from an aircraft flying in formation with the strike aircraft. Three canisters were released by the bombardier of the companion plane upon noting "first motion" of the bomb released from the strike aircraft.

Plans had been made to test this technique at Trinity, but safety considerations precluded the aircraft from being on station; however, ground-based measurements were made. The method was tested on a 100-ton high-explosive test prior to Trinity with good results and on the Crossroads test with good results on Able but with poor results on Baker. Able was an airburst at 520 feet, Baker was an underwater explosion at a depth of 90 feet. The yield derived from the canister data from the 100-ton and the Able explosions were in good agreement with those from other determinations. Since Baker was underwater, the poor agreement using the canister measurements is not surprising.

One good record was obtained on each combat mission (the signal went off-scale at Nagasaki); the record shows both the direct and reflected shock timed from the start of the record (about one second after bomb release).[6] In principle, the records contain enough information to determine the canister slant range and altitude. For the Hiroshima mission, historical records give the bomb drop altitude as 31.6 kft* and the canister altitude at shock arrival as 30.5 kft.[6−8] The latter was determined from the aircraft altitude, the fall rate of the canisters, and the time of arrival of the shock wave. They are consistent values. There were no altimeters in the canisters, but the bomb drop altitude can be deduced from the canister record to be about 35 kft and the canister altitude as about 34 kft. These are extreme values judged from the performance characteristics of the craft. The difference from the historical records has not been resolved. The canister data were recently reanalyzed by Kennedy et al[9] using meteorological data taken over Japan in August 1945. This data described the atmosphere and a combination of two- and one-dimensional hydrodynamic calculations in an attempt to match the timing of the record and the shock magnitudes. They put most reliance upon their calculations of the positive phase duration and the impulse. For these slant ranges and the low overpressures the method should not be sensitive to the canister location. Their yield estimate is 16.6 ± 0.3 kt. They quote an error (standard deviation) of 0.3 kt (i.e., 2%). This error is the precision of the calculation not the overall error, which must be greater than 10%. Their determination of the slant range from the explosion to the canister is greater than that obtainable from the historical records; thus their yield is probably an upper limit.

Blast Wave Damage

A group composed of W. G. Penney , R. Serber, and G. T. Reynolds, from the Manhattan District was sent to both Hiroshima and Nagasaki soon after the explosions to report on physical effects. Their surveys have provided much of the information upon which to make estimates of the yields of the two explosions. The results of the survey and samples of damaged objects from the blast wave were analyzed by Penney et al.[5] They concluded that the yield of the Hiroshima explosion was 12 kt with an estimated standard deviation of 1 kt (i.e., 8%). They used objects damaged by the pressure pulse and by drag.** Calibration was in terms of scale models in high-explosive scaled tests. Unfortunately the scale used was for a full-scale explosion at the Hiroshima height-of-burst but with a yield of about 10 kt, which requires an extrapolation for both explosions. They also assume ideal surfaces in the two cities. Probable large surface and terrain effects were not treated. Penney recently reevaluated their data using US height-of-burst data and found the same result.

Charring of Cypress

Charring of cypress wood on a shrine on the roof of the Chugoku Electric Power Building

*1 kft equals 1000 ft or approximately 914 m.

**An evaluation of the Hiroshima yield using the observation of damage to drag sensitive objects (lightning rods, flagpoles, etc.,) was made at Sandia Corporation in the early 1950s by Shelton (Private communication, 1984). Calibration was by scaled models placed in a supersonic wind tunnel. Documentation has not been located. The value of the yield obtained was 16 kt.

reported by Kimura et al[10] and again by Tajima[11] offers an evaluation of the Hiroshima explosion yield in absolute terms. It was observed that there were two charred layers, one a completely carbonized outer layer of 0.01 mm (1.38 mg/cm^2) and a brown, incompletely carbonized inner layer 0.35 mm thick. It was found that to produce the completely charred layer required 3.3 seconds exposure from a 1200°C electric hot plate. This is a thermal fluence of 21.1 cal/cm^2 assuming black-body radiation at that temperature. It was also observed that the thickness of the second layer was dependent upon the intensity of the radiation and not on the exposure time from a carbon arc furnace. To obtain the 0.35 mm thickness of the incompletely charred layer required 14 cal/cm^2 per second; with this rate it required 1.4 seconds to produce the 0.10 mm thick completely carbonized layer for an energy fluence of 19.6 cal/cm^2.

It was assumed that the energy impinging on a surface at slant range R was proportional to

$$W \cos i \, e^{-\epsilon R}/R^2 \tag{1}$$

where W is the yield, i the angle of incidence, and ϵ the extinction coefficient. The extinction coefficient may be obtained from the measured visibility by the relation $\epsilon = (\ln(50))/V$ used by meteorologists. V is the visibility and the Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs (CCMDCAB)[12] gives V as greater than 20 km and uses values of 20 and 30 km as the extremes for its calculations.

The distance to the Chugoku Electric Building from the hypocenter was about 676 m and the height of the building (and shrine) was 21 m giving a slant range of about 877 m. The transmission using a visibility of 20 km, the poorest according to CCMDCAB,[12] was about 0.84. The measured angle between the burst and the normal to the surface was given as 62° 36′. The fraction of the explosion energy allotted to thermal energy is generally taken as 0.35.[1] From these values the yield of the Hiroshima explosion must have been about 15.1 kt using the first calibration method or 14.0 kt using the second.

The evaluations neglect conduction and reflection effects. It was noted in the original article[10] that with the longer irradiation times from the calibrating source as compared to the weapon thermal pulse (time of maximum, t_{max}, was about 0.14 seconds; at 10 times this value or 1.4 seconds, 0.80 of the total was delivered) more heat is lost into the wood by conduction and the fluences obtained are upper values. Reflection from the surface is an opposing effect and would be greater from the bomb thermal radiation; the reflection coefficient probably varied from 0.7 to 0.05 during the irradiation. In an attempt to examine conduction, a calculation was made of temperature and energy fluence rate into the material using reasonable values[13] for the thermal parameters (conductivity $K = 2.8\times10^{-3}$ cal cm^{-1} s^{-1} °C^{-1}, density $\rho = 0.46$ g cm^{-3}, specific heat c = 0.40 cal g^{-1} °C^{-1}, and diffusivity $k = K/c\rho = 0.015$ cm^2 s^{-1}). The fluence rate peaks at about 1 t_{max} and the temperature at about 2 t_{max}. Penetration distance at 10 t_{max} is about 4 mm. The calculation assumed constant values and no phase changes (no equation-of-state was found). For a constant fluence rate from the calibrating source, an exposure time of 1.4 seconds, and a penetration depth of 4 mm, it was found that the fluence rate was down to 0.05 of the fluence rate at the surface versus about 0.01 for a bomb thermal pulse. Reflection from the surface opposes the conduction effect but no estimates have been made.

The average yield obtained by the two calibrations is 14 or 15 kt if the more reliable value from the completely charred layer is used. Repeat calibration using more modern thermal sources with approximately the proper time dependence would likely produce a better estimate from these data.

Gamma-Ray Measurements

Comparison of calculated gamma-ray doses with measurements of gamma-ray induced thermoluminescence in roof tiles provides an absolute way of determining yields. The dose at any given location is proportional to the yield, for the low yields of interest here; thus the yield employed in the calculation can be adjusted to give the best fit to the measurements. The yield for best fit becomes the new estimate of yield. The method assumes that there is no uncertainty in the model used in the calculations.

Confidence in this method is generated by the experience at the Los Alamos National Laboratory (LANL) where gamma-ray doses measured at ranges where hydrodynamic-shock enhancement and cloud-rise effects are small has long been used as one method of determining the relative yield of nuclear explosions. They measured the doses at a common range (2500 to 3000 m) with similar film badges housed in similar packages, corrected for any difference in atmospheric conditions, and then simply assumed the measured doses were proportional to the yields. Better agreement was obtained if the data were from similar explosive devices. The method has worked well for yields less than about 40 kt, where hydrodynamic effects are small.

Chapter 3 describes methods for calculating the gamma-ray doses from the bombs and Chapter 4 describes the thermoluminescent measurements that were made. Means of the fractional differences between the measured values and calculations made using yields of 15 kt for Hiroshima and 21 kt for Nagasaki are given in Tables 29 and 30 of Appendix 4-11.

The uncertainties on these relative differences are large. It is clear, however, that a systematic difference exists between the Japanese laboratories and the British and American laboratories. The Anglo-American measured values are higher at Hiroshima and lower at Nagasaki than those of the Japanese (something that cannot be removed by changing the yields used in the calculations). Also, the relative differences may change with distance (also something that cannot be removed by changing the yields). At Nagasaki, the measured values are generally about 10% too low; at Hiroshima, beyond 1000 m, they are too high by 10 to 25% according to the Japanese results or about 35 to 50% according to the Anglo-American results.

Appendix 4-11 deals with the question of how much of the difference between the results at the two cities can be attributed to aspects of the calculation other than the yield. Apparently little can be. Most changes proposed would affect doses in both cities about the same way.

The low values at Nagasaki are consistent with experience at weapons tests of bombs similar to that used at Nagasaki. Consequently, no recommendations were made in Appendix 4-11 for changing the doses at Nagasaki (i.e., there is no need to change the yield). The appendix did, however, recommend that the doses at more than 1000 m at Hiroshima needed to be increased by about the amount required by the Japanese data (10 to 25%) but not as much as required by the Anglo-American data (35 to 50%). It did not say that all of this change had to come from a change in yield (at Hiroshima); but, if these percentages were assigned to yield changes, they would imply yields of 16 to 19 kt at Hiroshima and 20 to 22 kt at Nagasaki. A value of 18 kt at Hiroshima was chosen to represent the results of these studies later.

Neutron Measurements

Comparison of calculated neutron doses with measurements of neutron induced ^{32}P radioactivity in sulfur used to bond insulators to utility poles gives another absolute way of determining yield. For weapons with similar leakage spectra, the doses are proportional to the yields, for the low yields of interest here; thus the yield employed in the calculation can be adjusted to give the best fit to the measurements. The yield for best fit becomes the new estimate of yield.

LANL has successfully used measurements of several different radioactivities, including $^{32}S(n,p)^{32}P$, to determine relative yields of similar sources in nuclear tests.

Chapter 3 describes the calculation of neutron fluence spectra. Chapter 5 describes the ^{32}P measurements made by Yamasaki and Sugimoto [14] and corrected by Hamada.[15] Figure 1 shows the corrected data and calculations for a yield of 15 kt. A least-squares comparison of these results indicates that the best fit would be obtained with a yield of 13 kt.

Equivalent Blast Effects Scaling

Subsequent to the explosions surveys were made to determine distance from the hypocenter at which similar effects in the two cities occurred due to the blast wave. The data available for comparison is limited but a few comparisons made by the same observers and with documentation do exist. Damage due to drag effects have been excluded. Only those comparisons of damage due to overpressure and with a significant number of objects observed have been retained. The ground surfaces were far from "ideal"; thermal effects would have produced a precursor to the blast wave and added both smoke and dust loads. In addition, mechanical effects due to the debris from the many buildings would have absorbed energy from the wave to further load the blast wave.[1] In a summary of blast data, however, Brode[16] suggested that simpler models of the height-of-burst effect may be appropriate. Two such models have been suggested: using scaled ground ranges and scaled slant ranges. These relations are:

$$W_H/W_N = [X_H/X_N]^3 \tag{2}$$

and

$$W_H/W_N = [R_H/R_N]^3 \tag{3}$$

where the subscripts refer to Hiroshima and Nagasaki, W to the yield, X to the ground range, and R to the slant range. Scaling by ground range allows for some height-of-burst effects independent of height-of-burst.[1] Scaling by slant range implies that the effect of the direct shock results in more damage than does the reflected shock. Both postulates have the same dependence on yield of the cube of the distance. Both postulates predict a circular pattern

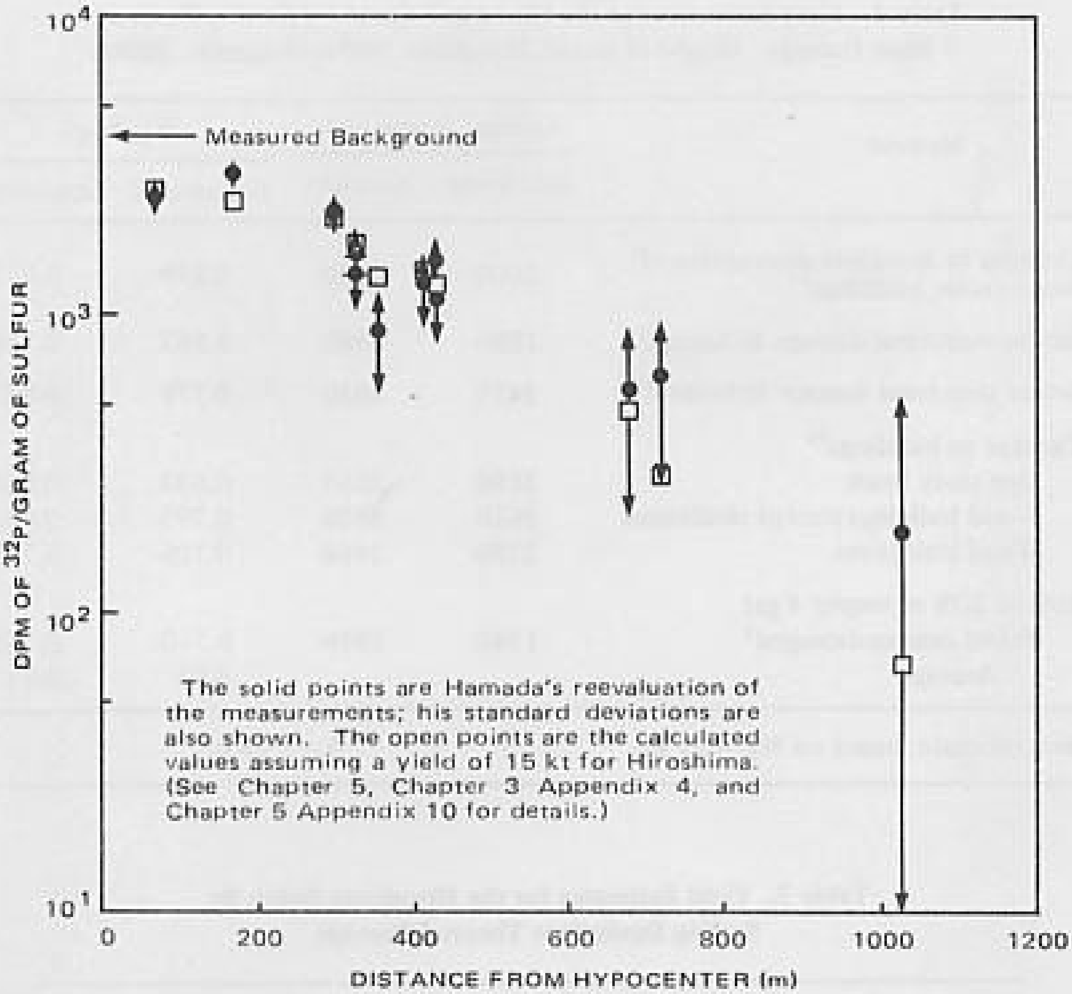

Figure 1. Sulfur activation at Hiroshima

of damage on the ground under the bomb, although the observed patterns are irregular and somewhat elongated. Brode prefers the first model, but the second appears to us to be more appropriate.

Table 2 gives the data set and the derived yields for Hiroshima based on a Nagasaki explosion yield of 21 kt.[5,17–19] We believe the petrol-can data are the most credible, with the damage to buildings next best. The average for the Hiroshima yield is 14.3 kt using ground range scaling and 14.9 kt using slant range scaling. The average of these is 14.6 kt or 15 kt when rounded.

Equivalent Thermal Effects Scaling

Surveys subsequent to the explosions noted distances from the hypocenter at which similar effects due to thermal radiation occurred in the two cities. The data set is limited, but four documented comparisons by the same observers in the two cities were selected by Kerr.[3] The same set is used here. It was assumed that the energy impinging on an object is proportional to Equation (1). All surfaces were taken as vertical except for the roof tiles which were assumed normal to the incident radiation. Table 3 gives the ratios of the yields (W_H/W_N) determined from thermal effects[5,19–21] using a visibility of 20 km, the poorest visibility used in calculations in CCMDCAB.[12] The average value obtained is 0.64. Taking the Nagasaki explosion yield as 21 kt gives a yield for the Hiroshima explosion of 13.4 kt.

Table 2. Yield Estimates for the Hiroshima Bomb by Scaling Equivalent Blast Damage. Height of Burst: Hiroshima, 580m; Nagasaki, 500m.

Method	Ground Range (m)		W_H/W_N	
	Hiroshima	Nagasaki	Equation 2	Equation 3
Collapse or complete destruction of wood-frame buildings[17]	2000	2400	0.579	0.612
Severe structural damage to homes[18]	1980	2440	0.562	0.568
Severe structural damage to homes[17]	2410	2620	0.778	0.802
Damage to buildings[19]				
One story brick	2190	2550	0.633	0.662
Wood buildings except residences	2610	2820	0.793	0.813
Wood residences	2190	2460	0.706	0.735
10% to 20% of empty 4 gal				
Petrol cans undamaged[5]	1740	1950	0.710	0.755
Average			0.68	0.71
Best estimate, based on W_N = 21 kt,		W_H = 15 kt		

Table 3. Yield Estimates for the Hiroshima Bomb By Scaling Equivalent Thermal Damage

Method	Ground Range (m)		W_H/W_N
	Hiroshima	Nagasaki	
Melting of roof tiles[20]	600	950-1000	0.575-0.526
Exfoliation of granite[20]	1000-1100	1600	0.473-0.545
Charring of poles[21]	2740	3050	0.782
Charring of poles[5,19]	2900	3350	0.707
Average			0.64
Best estimate, based on W_N = 21 kt,		W_H = 14 kt	

If a 30 km visibility were used (the best used in CCMDCAB[12]), the derived yield is about 13.7 kt. The exfoliation of granite observations are highly subjective; omitting them results in a ratio of 0.68 or a yield of 14.3 kt. The best we can do with the thermal comparisons is to say they imply a yield of about 14 kt.

The Yield of the Hiroshima Bomb

The yields for the Hiroshima bomb, derived by the various methods, are given in Table 4. Also given are weighting factors chosen by us to indicate, in a rough fashion, the degree of confidence we have for each method. The mean (rounded) of the values in the table is 15 kt, both with and without the weighting. We feel, therefore, that 15 kt is a reasonable choice for the yield of the Hiroshima bomb.

Table 4. Yield Estimates for the Hiroshima Bomb

Method	Yield	Weight
Absolute methods		
Thermoluminescence	18	3
Pressure vs time	16	3
Cypress charring	15	2
Sulfur activation	13	1
Blast damage	12	1
Relative methods		
Thermal effects	14	3
Blast effects	15	1
Theoretical calculation	15	2
Weighted average	15	

CONCLUSIONS

The recommended yields for the two explosions are Hiroshima 15 kt and Nagasaki 21 kt where the value for the Hiroshima yield is believed to have an outside limit of uncertainty of 20% and that for Nagasaki of 10%. For estimating the propagation of errors, we believe these limits can be taken to represent 2.3 or 2.4 standard deviations.

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