in Nagasaki.

2. Fire Protection

a. Fire Departments. Both Hiroshima and Nagasaki were poorly prepared to combat a conflagration of large-scale proportions, although preparations had been made in both cities to combat mass incendiary attacks. Private fire equipment had been augmented and citizens had been given limited instructions and training in handling incendiary bombs. On the other hand, the public fire departments, which had proved adequate in controlling normal peacetime fires, had not been improved. In fact, in Nagasaki the professional fire-fighting personnel had been reduced 40 per cent. Even in peacetime, however, Nagasaki placed more reliance on auxiliary fire-fighting equipment and personnel than did Hiroshima. Interurban assistance at both cities was quite limited because there were few near-by towns or cities of any size. Industrial plant fire departments, including equipment and personnel, were poor by American standards for cities of comparable size.

b. Water Supply. Both cities had combined domestic and fire-service water systems. Water pressure in the central part of each city was normally 40-45 pounds per square inch, but in some places pressure was as low as 5-15 pounds per square inch. Nagasaki had a reservoir capacity of 740,000,000 gallons compared to 4,500,000 gallons in Hiroshima. The water at Hiroshima, however, was pumped from the Ota River, providing an inexhaustible supply, and 20,000,000 gallons of filtered water could be furnished daily. Water flowed to the cities by gravity, booster pumps furnishing the pressure for some areas.

Sizes of water mains and branch lines were comparable in the two cities. Most of the hydrants in both cities were of the below-ground type.

c. Fire Breaks. The Ota River and its six branches divided Hiroshima into nine distinct areas. These river courses and 41,000 feet of fire lanes, which had been prepared by removing combustible buildings on one or both sides of fairly wide streets, provided the city with probably the most extensive network of fire breaks per square mile of any city in Japan. An elaborate system of fire breaks, totalling 55,000 linear feet, had also been cleared in Nagasaki to augment the natural fire breaks provided by Nagasaki Bay and the Urakami and Nakashima Rivers.

3. Start of Fires

a. Hiroshima. The explosion of the atomic bomb at Hiroshima started hundreds of fires almost simultaneously throughout the heavily built-up city center. The original fires were most numerous within 4,000 to 5,000 feet of Ground Zero, since the buildings in this area were closer to the center of heat, there were more of them, and a larger percentage was collapsed by blast. The temperature at the center of the bomb explosion was of extreme intensity (estimated at 70,000,000° C), but because the heat had largely dissipated before reaching ground objects, the temperature at Ground Zero probably was only in excess of 3,500° C for a fraction of a second. Apparently this flash heat started numerous fires in easily ignitible materials such as dark cloth, thin paper, and dry-rotted wood, principally within 3,500 feet from Ground Zero. Most of the initial fires, however, were started by secondary sources of ignition, such as kitchen charcoal fires,

electric short circuits, and industrial process fires, through the collapse of combustible buildings and in debris created by blast.

b. Nagasaki. The Nagasaki bomb was more powerful than the Hiroshima bomb and was detonated somewhat nearer to the ground. For these reasons the intensity of the heat at Ground Zero exceeded that at Hiroshima, and, in proportion to the amount of combustible materials exposed, radiant heat from the Nagasaki bomb is believed to have started more fires. In addition, there were hills within 2,000 feet of Ground Zero which placed buildings, trees, and other objects on them closer to the point of detonation, and directly exposed a greater proportion of the interiors of the buildings to radiant heat from the bomb. Wooded hillsides 1,000 to 2,000 feet west of Ground Zero in Nagasaki were ignited by radiant heat. In both cities exposed, vitreous roof tiles were blistered, granite was spalled and roughened, and wood, asphalt, and asphalt-painted surfaces were flash burned at various distances from Ground Zero depending upon their susceptibility to heat.

4. Fire Spread. There was a relatively small amount of fire spread in both cities beyond the areas in which the original fires were ignited by radiant heat from the bomb and secondary sources. A fire storm, including both wind and rain, developed in Hiroshima soon after the start of the original fires. The wind, which blew from all directions toward the burning area, reached a maximum velocity of 30 to 40 miles per hour about two to three hours after the explosion. Light and heavy rain fell intermittently over the north and west parts of the city. The fire storm was a decisive factor in limiting fire spread in

directions away from the city at the fire perimeter. The high winds were caused by the fires drawing in a fresh supply of oxygen over the flat terrain, and the rain resulted from the condensation of moisture on particles of hot carbon which had been blown northwestward by the light, natural, southeast wind. Although a distinct fire storm did not develop in Nagasaki, the velocity of the southwest wind, directly up the bay between the hills, had increased to about 35 miles per hour when the conflagration had become well established, probably about two hours after the explosion. About nine hours after the explosion the wind had shifted to the east, but its velocity had diminished to 10 to 15 miles per hour. The southwesterly wind is believed to have assisted in stopping fire spread to the south on both sides of the bay, and the shift of the wind to the east may have limited fire spread in the Nakashima River valley. No rain was reported to have fallen over the city. The long, narrow shape of the Urakami River valley and the hills which lined both sides of it were not so conducive to development of a fire storm as the broad flat terrain of Hiroshima. There was a natural tendency for the fires to sweep up the hills, which they did, and to draw a fresh supply of air from the south up the center of the narrow area formed by the river and the sites of noncombustible industrial plants on its east bank. This narrow corridor varied in width from 500 to 2,000 feet, and extended from just southwest of Ground Zero all the way south to the bay. Apparently it acted as a funnel through which a fresh supply of air from the south could reach the burning areas on each side of the Urakami River, and this accounted for the great increase in wind

velocity from the southwest. Except in Nagasaki where the fires swept up the hills on both sides of the Urakami Valley, there was no evidence of a general advancing front to the conflagration in either city. At Hiroshima, however, there was some fire spread beyond 5,000 feet from Ground Zero in built-up areas outside the periphery of the original fires. A large proportion of the burned-over areas in both cities resulted from the spreading and merging of the original fires. In Hiroshima most of the fire had burned itself out or had been extinguished in the fringe area about 12 hours after the explosion. In Nagasaki most of the fires had died out or were under control about 19 hours after the explosion. Isolated fires continued to burn and smoldering persisted over a large part of the burned-over areas in the two cities for three or four days. In fact, grain in three warehouses in Hiroshima burned for several weeks.

5. Fire Fighting

a. Effort. Almost no effort was made to fight the conflagrations within the areas finally burned over except in a few reinforced-concrete buildings where the occupants remained or where people took refuge. At Hiroshima the fire wind blowing toward the city from all directions was a major factor in checking fire spread at the perimeter. In both cities, the more sparsely built-up areas, some of the wider streets, and a limited amount of fire fighting assisted in stopping fire spread at the perimeter. Fire breaks at Hiroshima were ineffective because the original fires were ignited on both sides of them, but at Nagasaki man-made fire breaks (9,000 and 11,000 feet southeast of

Ground Zero) combined with bucket-brigade activity stopped the spread of fire at two locations.

b. Difficulties Encountered. Within 5,000 feet of Ground Zero in all directions at Hiroshima, a large proportion of the serious casualties occurred. Thousands of persons were killed immediately by the explosion and additional thousands were injured, many critically. Approximately 70 per cent of the public fire department apparatus was immediately out of service, and over 80 per cent of the "on-duty" firemen were killed or incapacitated. Almost none of the "off-duty" firemen, who would normally be available, reported for duty. Thus, the public fire department had been dealt an instantaneous, paralyzing blow from which it could not recover. The streets were blocked by demolished buildings and their contents, debris covered a majority of the underground hydrants, and the general confusion was tremendous. Even if the fire department had remained intact, the general situation within 5,000 feet of Ground Zero would have been a hopeless one from the beginning. At a few places on the fire perimeter the public fire department performed some effective work but its efforts played a minor role in the over-all fire-fighting task. The most effective fire fighting was done by the civilian populace, aided by soldiers who were quartered in the area, who formed bucket brigades and passed buckets of water from tanks, open drainage ditches and rivers. One 16-inch water main was broken by the collapse of the bridge which carried it; the booster pumping stations were damaged by blast; and large numbers of small feed lines were broken by the collapse of the buildings they

served. An immediate reduction of water pressure in the system resulted. Later in the day the distribution system in the center of the city was shut off. The reservoir did not run dry and lack of water in the public water system apparently had no effect on the fire situation. It would have failed, no doubt, if a heavy demand had been placed on it. In Nagasaki, extensive and serious blast damage to buildings and casualties to persons were limited to within 7,000 feet of Ground Zero in the Urakami Valley. The Nakashima Valley was shielded from the blast by 900-foot hills, 6,000 feet southwest of Ground Zero. Consequently the public and volunteer fire departments escaped with only 35 per cent of their personnel killed or injured and 20-per-cent total damage to their pumping engines. These losses were light compared to those at Hiroshima. Except for minor casualties, the fire-fighting organization beyond 7,500 feet south and southeast of Ground Zero remained intact. The fire chief dispatched two pumping engines from the main fire station (9,500 feet southeast of Ground Zero) to combat the fires to the north, and dispatched men to establish liaison with the volunteer fire departments as telephone communications had been disrupted. One truck penetrated to the vicinity of the gas works, 6,500 feet south of Ground Zero, arriving there about 10 minutes after the explosion, but it could go no farther because streets were obstructed by debris and buildings in the area to the north were in flames. This truck returned to the main fire station to assist in fighting fires in that vicinity. The public and volunteer fire departments fought against spread of fire within the area between 8,000 and 11,000 feet south of Ground Zero on

the east side of Nagasaki Bay and in the area between 6,000 and 8,000 feet south of Ground Zero on the west side of the Urakami River, although seriously handicapped by decreasing water pressure in the city water system which finally became too low to be of use for fire-fighting purposes within 18 hours after the explosion. The blast caused five breaks in a 12-inch cast-iron main three feet below grade in a reclaimed area within 2,000 feet of Ground Zero by unevenly depressing the soil, and caused six additional major breaks, four of them by displacement of bridges which carried the pipes. Another contributing factor to the failure of the water supply was the breakage of several thousand service pipes resulting from collapse of buildings by blast or damage by fire. As in Hiroshima, bucket brigades utilizing water from tanks, wells, and water courses were most effective in limiting fire spread in fringe areas.

6. Extent and Cause of Fire Damage

a. Areas Involved. In Hiroshima a roughly circular area of 4.4 square miles was completely burned over. In Nagasaki an irregularly shaped area of 0.9 square miles was burned over on both banks of the Urakami River and on the north bank of the Nakashima River. There were few combustible buildings and fire-resistive buildings with combustible contents remaining unburned within the burned-over areas in both cities. The most distant extremities of the burned-over areas were 10,200 feet to the north and east from Ground Zero in Hiroshima, and 11,200 feet to the south from Ground Zero in Nagasaki. The shape and position of the fire pattern in each city were the result of the location of the bomb

burst and the characteristics of the terrain and built-up areas.

b. Radiant Heat Ignition. The ability of radiant heat from the atomic bombs to ignite combustible materials was of much interest. In both cities fire-resistive buildings with combustible contents were selected for study because these buildings suffered less structural damage and had fewer casualties, so that better visual and oral evidence could be obtained. In Hiroshima, it was established that radiant heat from the bomb was the probable cause of initial ignition in 20 per cent of the fire-resistive buildings, all of which were within 6,500 feet of Ground Zero. Comparable figures were not available for Nagasaki. It has been estimated, however, that in Nagasaki 90 per cent of all initial fires in fire-resistive buildings within 4,000 feet of Ground Zero might be attributed to radiant heat; in comparison, only about 30 per cent of such fires in similar buildings in Hiroshima within 4,000 feet of Ground Zero were caused by radiant heat. Although the Nagasaki bomb was reported to have been more efficient than the Hiroshima bomb, there is considerable doubt about the 3-to-1 advantage indicated for its effectiveness as a source of direct ignition.

c. Fire Spread. Despite the fact that radiant heat started more fires in fire-resistive buildings in Nagasaki than in Hiroshima, a higher percentage of the buildings in Hiroshima was affected by fire and sustained more extensive fire damage, evidently as a result of fire spread. In Hiroshima a large proportion of the fire-resistive buildings comprised offices, banks, stores, and warehouses which were located in congested, combustible areas, whereas similar structures in Nagasaki

were principally school, college, and institution buildings, most of which were in groups or set off by themselves and not closely exposed to congested, combustible areas. In Nagasaki all of the 31 fire-resistive buildings which sustained fire damage were within or adjacent to the burned-over area and within 4,000 feet of Ground Zero, whereas in Hiroshima only 69 per cent, or 40 buildings, were within 4,000 feet of Ground Zero. In order to demonstrate that there was more fire spread to fire-resistive buildings in Hiroshima than in Nagasaki, the following comparison is presented: TABLE 38

Fire-Resistive Buildings	Nagasaki	Hiroshima
No. of buildings within or adjacent to burned-over area and within 4,000 ft of GZ	37	41
No. of buildings involved by fire within 4,000 ft of GZ	31	40
Percentage of buildings involved by fire within 4,000 ft of GZ	82	98
Percentage of total floor area burned within 4000 feet	52	89
Percentage of buildings involved in fire within or adjacent to entirely burned-over area (max dist 6,500 ft from GZ)	--	91
Percentage of total floor area burned within 6,500 ft from GZ	--	72

d. Effect of Exposure Distance on Fire Spread. In Hiroshima, a special study of exposure distances at 107 burned and 23 unburned fire-resistive, noncombustible, and combustible buildings, and 8 burned and 7 unburned combustible bridges within or adjacent to the burned-over area led to the conclusion that there was a relationship between

incidence of fire in the buildings and bridges and their distances from burned exposing buildings. Fire definitely failed to spread by exposure to only one fire-resistive and one noncombustible building among the 107 buildings which were burned. The study is summarized as follows:

TABLE 39

Combustibility Classification	Average distance (ft) from nearest exposing bldg from which fire spread may have occurred	No. of Cases	Average distance (ft) from nearest exposing building from which fire spread did not occur	No. of Cases
Fire-resistive bldgs	20	57	90	7
Noncombustible bldgs	5	7	30	5
Combustible bldgs	20	41	40	13
Average for all bldgs	20	105	50	25
Combustible bridges	35	8	70	7

(A similar study was not conducted in Nagasaki)

At Hiroshima studies were also made which established a relationship between probability of fire spread and built-up density, and between probability of fire spread and exposure distances for the conflagration. The results indicated that there was a rapid increase in probability of fire spread as built-up density increased above 12 per cent and as exposure distances decreased below 50 feet; and that there was a comparatively small return in immunity from fire spread among combustible buildings averaging one and a half stories with a decrease in built-up density below 12 per cent and an increase in exposure distance above 50 feet.

e. Contributive Effects of Blast to Fire Damage. Within the areas finally burned over in both cities, the bomb blast rendered most buildings of all fire classifications extremely vulnerable to spread of fire by exposure by breaking all glass and blowing in or damaging fire shutters, stripping wall and roof sheathing, and collapsing walls and roofs. Likewise, it left practically all buildings in a condition extremely favorable to internal fire spread by blowing off or damaging doors at stairs, elevators, and fire walls, blowing down partitions, and rupturing and collapsing floors. In fire-resistive buildings, with almost no exceptions, fires spread upward, and in about two-thirds of the cases also spread downward, as indicated by burned basements in Hiroshima.

f. Comparison of Fire and Blast Damage

(1) Fire-Resistive Buildings. Except in three buildings in Hiroshima, all structural damage to fire-resistive buildings in both cities was caused by blast. On the other hand, fire damage to the interiors and contents of fire-resistive buildings greatly exceeded damage by blast and debris. Most of these buildings had combustible interior construction as well as a considerable amount of combustible contents, and combustion in the parts of the buildings which burned out was practically complete. Structural damage to the three fire-resistive buildings in Hiroshima was the result of intense heat of long duration which was dependent

upon the nature of the contents (grain in two cases, and books in the other) and confinement of the heat.

(2) Noncombustible Buildings. In both cities noncombustible buildings, most of which had steel frames sheathed with corrugated iron or corrugated asbestos, were structurally damaged principally by blast. In Hiroshima, where most of these buildings were small and all had light, steel frames, a major part of serious damage to contents was caused by fire. In Nagasaki the noncombustible buildings were comparatively large and were approximately equally divided among heavy and light, steel-frame construction. Fire caused no serious damage to contents in the heavy, steel-frame buildings and a very small amount of serious damage in the light, steel-frame buildings. About 50 per cent of the noncombustible buildings in Hiroshima had combustible contents whereas most of those in Nagasaki had noncombustible contents.

(3) Combustible Buildings. Combustible buildings in both cities were structurally damaged principally by blast, but it is believed that fire caused the majority of severe damage to contents. After sustaining damage of varying degrees by blast, approximately 50,000 of 90,000 combustible buildings in Hiroshima and approximately 13,000 of 55,000 combustible buildings in

Nagasaki were totally damaged by fire.

(4) Bridges. In Hiroshima eight of 15 combustible bridges within or adjacent to the burned-over area were heavily or totally damaged by fire, three after having been damaged initially by blast. Each of the eight bridges was ignited by spread of fire from near-by combustible buildings. In Nagasaki one combustible bridge was totally damaged by fire after sustaining blast damage. This bridge probably was ignited by flaming debris from burning buildings. Combustible bridges located outside the burned-over areas sustained no fire damage, and concrete and steel bridges, wherever located, were not damaged by fire alone in either city.

7. Comments.

a. Hiroshima was an excellent test target for the atomic bomb from a fire standpoint principally because the shape of the densely and and moderately built-up areas was roughly circular over broad, flat terrain which was cut up by an extensive network of rivers and man-made fire breaks. The maximum return in fire damage was obtained in Hiroshima because the bomb detonated over the heart of the city.

b. Nagasaki. Although the shapes of the built-up areas of Nagasaki were very irregular, lying on the narrow shores of, and in the valleys extending out from, Nagasaki Bay, it was an excellent test target for the atomic bomb from a fire standpoint because its urban areas

were extremely congested and combustible, and the bay and the Urakami River were extensive fire breaks. The maximum return in fire damage was not obtained, however, because the bomb detonated too far to the north. It is believed that the burned-over area in Nagasaki would have been doubled, and possibly tripled, if the bomb had been detonated at approximately the same altitude but 6,500 feet directly south of Ground Zero, where a large proportion of the central and eastern parts of the city in the Nakashima Valley, and the north, southeast and southwest parts of the city as well, would have been directly exposed to the blast and heat effects of the bomb.

c. Effect of Terrain. The shape of the burned area in Hiroshima leads to the conclusion that the detonation of an atomic bomb over the center of any flat, uniformly built-up, combustible city would result in a roughly circular area of fire damage, provided there was no more than a light, natural ground wind. The shape of the burned area in Nagasaki illustrates the effect of shielding in limiting the extent of fire damage, at least in the presence of a light, natural ground wind.

CHAPTER VII

STRUCTURAL CONSIDERATIONS

1. Early Conclusions Sustained. The Japanese survey afforded an opportunity to re-examine the structural conclusions stated in the European report of the Division (PDD 68). The second survey disclosed no reasons for changing the following conclusions of the first:

a. Blast Loading. When a bomb detonates inside a building, the slab, beams, and columns above the point of detonation are subjected to loads in the opposite direction from those for which they were designed. Where the principal framing members were of steel this reversed loading was of small consequence. Reinforced-concrete members, on the contrary, were unable to resist such reversals. In particular, columns failed by pulling apart at regions where reinforcing rods were lapped, and beams failed along the planes where main rods were bent to furnish resistance to diagonal tension. The use of a small amount of negative reinforcement throughout the length of a beam and the use of vertical stirrups instead of bent rods for "shear" reinforcement would greatly strengthen a beam against reversed loads.

(1) Trusses, or, in general, open-web members, were less damaged by direct hits and blast than were girders (i.e., solid-web members).

(2) Continuity and bracing were of considerable value in limiting the extent of spreading collapse.

(3) Wall-bearing structures and the so-called slow-burning mill-type with poor connections between

beams and columns were the poorest types from the standpoint of bomb resistance.

(4) In multi-story construction the damage to steel structures was less widespread than in those of reinforced concrete; the former would also be far easier to repair.

(5) Field-riveted structures appeared to have no advantage over those that were field bolted. Data are still lacking on the action of welded structures.

(6) Asbestos Sheathing. Buildings roofed and sheathed with corrugated asbestos suffered little distortion or damage to the structural frame even when relatively close to the point of detonation of a high-explosive bomb (or, as may now be added, an atomic bomb), since the asbestos shattered so quickly that little force was exerted on the frame. Fire caused little further damage because there was nothing to confine the heat.

b. Concrete Structures. Although the earlier conclusions regarding the effects of high-explosive bombs on reinforced-concrete structures were confirmed, it should be made clear that relatively little additional information was obtained on these effects for the following reasons:

(1) The Japanese had no structures of the heavy bunker (shelter) and submarine-pen types.

(2) High-explosive bombs were dropped, in general, only on industrial plants and these had comparatively few reinforced-concrete buildings.

(3) The reinforced-concrete buildings of Japan were largely multi-story structures which were concentrated in cities, and Japanese cities were attacked only with incendiary bombs.

On the contrary, a vast amount of information was collected on the effect of the atomic bombs on reinforced-concrete structures. Detailed examples of such damage are given in profusion in the Division's reports on Hiroshima and Nagasaki.

c. Steel Structures. The great majority of high-explosive-bomb incidents reported on in Japan dealt with steel structures, most of which compared favorably with typical American structures in the strength of both their main members and connections. Hence, the MAE figures which are presented in another chapter of this report may be considered applicable to structures in the United States.

2. New Considerations (Anti-Atomic-Bomb Construction). Probably no structure could withstand the near detonation of an atomic bomb. Such a conclusion, however, should not obscure the fact that precautionary measures can measurably decrease the effects on structures which are moderately removed from the bomb. It will be understood that conclusions reached in this report are based on the

observed effects of two particular bombs. Differences which might result from different types of atomic bombs, when and if such are developed, have not been considered.

a. Military. A structure designed to be bomb proof against a 2,000- or 4,000-pound, high-explosive bomb would probably be resistant to any except a very near miss of an atomic bomb.

(1) There is an imperative need for an experimental underground detonation of an atomic bomb. Such a test may disclose that at moderate distances a structure on the surface is superior to a sub-surface structure.

(2) Important structures should be dispersed to reduce the attractiveness of a target.

(3) Vital posts should be built (suitably separated), equipped, and manned in duplicate.

b. Urban. Studies in progress, to be reported on by medical groups, will tell how much cover of reinforced concrete or other material is needed to protect against the radiation effects of the atomic bomb. Assuming adequate warning of an attack, this information will enable a shelter policy to be evolved. Admittedly, if entire city populations are to be protected, the extent and cost of such a policy stagger the imagination.

(1) Curtain walls in skeleton construction constitute a great hazard. A poured-and-attached wall will increase the blast loads on a building frame but

is to be preferred to a wall of relatively loose units.

(2) In time of danger, load-bearing brick-wall buildings and combustible construction must be especially shunned. Perhaps the time has come to search for and require for future construction a type of common residence which will possess bomb-resistant qualities that far exceed those of the present prevalent types.

(3) Japanese residences, predominantly of wooden construction, fared as follows under the atomic bomb, distances being radii from Ground Zero:

Complete collapse	2,500 feet
Damaged beyond repair.	5,200 feet
Uninhabitable without extensive repair	7,500 feet
Uninhabitable without first-aid repair	8,000 feet

From knowledge of the effects of the German blits on their cities, British experts have concluded that the above distances would also apply to British residences in an atomic-bomb attack. There is no reason to suppose that American homes would fare any better.

c. Industrial. The superior type of structure is one with a sturdy frame of steel or reinforced concrete, covered with friable siding and roofing.

(1) Close-at-hand shelters (similar, perhaps, to the industrial and urban bunkers which were built by the Germans (FDD 22) must be provided for workers.

(2) A supply of covers (i.e., tarpaulins) must be provided to give equipment immediate protection against weather.

(3) Different plants must be separated by enough distance to insure that several plants could not be involved in a single bomb incident.

3. Comparison of High-Explosive Bomb Sizes. This Division caused to be written in the Survey's "Over-All Report (European War)" the statement: "As yet no final answer may be given on the relative merits of the small and large bomb when dropped on the usual industrial target." It is probable that this statement would be altered by every observer who visited both theaters; indeed, by those who visited Japan only. In the Japanese theater the 4,000-pound bomb (unused in Europe) was measurably superior as a blast weapon to any other, pound for pound. Photos and show the difference between the gnawing action of four 500-pound bombs and the blast action of a 4,000-pound bomb. In general, there was a steady gain in efficiency in going from the light bombs up to the 4,000-pound size. Any tendency to conclude that this gain would continue indefinitely

was stopped by the fact that the single heavier bomb for which data were obtained, that is, the 10,000-pound bomb, was again clearly inferior (pound for pound) to the 4,000-pound bomb.

4. Outstanding Structural Incidents. A number of impressive pictures of structural action were observed which merit brief mention.

a. An L-shaped, three-story, reinforced-concrete school at Nagasaki received the full blast of the atomic bomb on the outer face of one leg. The pressure was sufficient to cause the heavy columns, each approximately one foot by six feet, on the inner face of the other leg to fail in shear in the ground story (Photo).

b. A reinforced-concrete T-beam bridge at Hiroshima lost a bent in the flood which followed the hurricane. The adjacent bent was also severely damaged, but one-half of the roadway remained in position and continued to carry unrestricted traffic (Photo). Nothing was learned, unfortunately, about the details of the reinforcing.

c. A number of reinforced-concrete stacks were seen which continued to stand after losing a large part of their cross section. Perhaps the most impressive example was a stack at the Mitsubishi Aircraft Plant (Target 90:20-193) at Nagoya, which is shown in Photos herewith.

d. Structures were encountered which possessed amazing stiffness after portions of their supports were severed or removed. Large sections of steel buildings stood without apparent distortion after columns were cut (Photo); others after footings were

blown from under columns. Likewise, portions of reinforced-concrete structures remained in positions after great holes had been blown in their lower sections. Photo illustrates an example where the interior columns of a three-bay-wide building were severed, as were also a corner column and the sections between windows, but the third-floor-and-roof section cantilevered out from the undamaged part. Photo shows another example at the other end of the same building.

e. Buildings somehow hung together when portions were undermined by bombs. Photo illustrates a bay and a stairwell which were lowered by cratering bombs.

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UNITED STATES STRATEGIC BOMBING SURVEY

(Pacific)

PHYSICAL DAMAGE DIVISION

REPORT 75

Report on Physical Damage in Japan

(Final Report)

Dates of Survey: 15 October 1945 - 1 December 1945

3

ACKNOWLEDGMENT

The following report has been prepared not as a series of separate studies but as a concise, over-all summary of physical damage in the Pacific Theater of Operations. All of the factual information contained therein was secured by investigations in the field by this Division or other divisions of the Survey. This report is the composite result of the free interchange of data and ideas among all those who participated in planning and executing the mission. No attempt will be made to name here all those--over one hundred--who gathered in the field, often under arduous circumstances, the information for the 4 volumes, comprising 32 incident reports, and the reports on Hiroshima and Nagasaki of 3 volumes each, published by the Division, and who were named in the individual reports. It is, nevertheless, appropriate to identify the following who carried a large part of the responsibility:

Lt. Col. C. R. Chapman Ord, Chief of Division, and the following successive Executive Officers, Maj. L. N. Stead CWS, Lt. Col. J. H. Ahrens AGD, and Maj. J. F. Bangham, Jr. AC; Col. E. R. Closson Inf, who succeeded to the post of Chief of Division and who had the responsibility of editing and preparing the Division's reports for publication. Drafts for sections of this present report were prepared by

Prof. L. A. Brothers, Maj. W. J. Sanborn CWS,

Lt. Comdr. C. B. Walker USNR, Capt. E. R. Hjortsberg

FA, Capt. A. E. Fessel QMC, 1st Lt. P. Alter AC,

Mr. G. Hartman, Sgt. C. V. Humphreys.

Alike to them and to the unnamed personnel of the Division sincere thanks are due for untiring and faithful service.

Harry L. Bowman, Director

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CHAPTER I

INTRODUCTION

1. This over-all report on physical damage in Japan presents a summary of damage to structures, machine tools, utilities, bridges, stacks, and services caused by high-explosive bombs, incendiaries, and atomic bombs. Although many of the basic conclusions derived from the effects of aerial warfare studied in the European Theater and reported in Physical Damage Final Report 68 required no change as a result of the Japanese survey, additional conclusions have been evolved based on new variables, such as type of construction, method of attack, and types and combinations of weapons used. And, of course, the advent of the atomic bomb opened up entirely new and hitherto unexplored fields of research.

2. In making studies of the damage effected by high-explosive bombs, the principal efforts of this Division were directed toward relating a specific weapon to the damage it caused in particular types of buildings. A crushed target, therefore, was avoided as an unpromising object of study, and, for that reason, the report does not give as complete a picture of high-explosive damage as it does of incendiary-bomb and atomic-bomb damage. Likewise, the limited time which was available to the Survey for its work in the field prohibited a summation of the total industrial damage achieved by high-explosive weapons. It is probable that photographs already in the files of the Air Force will permit such a study to be made in the

future.

3. Better information was obtained on the effect of bombing on construction than on production. The fact that the Japanese made no real effort to repair their buildings or to get back into production after being bombed limited the opportunities of assessing accurately the effects of bombing on a more determined and resourceful enemy. At many plants production ceased after bombing without regard to the real effectiveness of the attack. Some plants were out of production before they were bombed, either because the flow of raw materials to the plants had stopped, or because the Japanese, fearing an attack, had started to disperse plant equipment and machinery.

4. The fire attacks on Japan went through a trial-and-error period in the early days, during which tactics were developed which culminated in the highly successful incendiary attacks on Tokyo and other cities. Unlike incendiary attacks on Germany, few or no high explosives were mixed with the fire bombs, since the flimsily built dwellings grouped in densely populated and congested areas were extremely vulnerable to saturation attacks and required no high explosives to "open them up." This fact, together with other favorable circumstances which were under the control of neither the attacker nor the attacked contributed to an incendiary campaign that was completely successful in almost every case.

5. The atomic bomb changed the character of the studies inasmuch as it was now a question of relating that type of bomb to the damage it caused in <u>all</u> types of buildings under two sets of circumstances

which were generally similar. Its blast effects were not unlike those of conventional high-explosive weapons, although considerably intensified and more widespread. The new factors of flash heat and radiation are likewise considered in this report.

6. Although a large number of the incident reports prepared by the Division include sections which compare a damage analysis made by photo interpretation with an analysis made by field teams, this general report does not contain a photo interpretation chapter similar to that found in the European report of the Division. The departure from the prior report is accounted for by the fact that in Europe the only information obtained by the Survey on photo interpretation was gathered by this Division, whereas in Japan a separate division of the Survey was concerned solely with this problem.

7. To readers who are interested in detailed analyses of physical damage in Japan, the following reports of this Division are recommended:

Number	Title
69	Effects of the Atomic Bomb on Hiroshima (Secret)
70	Effects of the Atomic Bomb on Nagasaki (Secret)
71	Effects of the 10,000-Pound Bomb on Japanese Targets. A Report on Nine Incidents.
72	Effects of the 4,000-Pound Bomb on Japanese Targets. A Report on Five Incidents.
73	Effects of the 500-Pound, 1,000-Pound, and 2,000-Pound High-Explosive-Bomb Attacks, including One Incendiary-Bomb Attack, on Selected Targets in Japan. A Report on Eight Incidents.
74	Effects of Incendiary-Bomb Attacks on Japan. A Report on Eight Cities.

3

CHAPTER II

EFFECTIVENESS OF HIGH-EXPLOSIVE BOMBS

A. SUMMARY

1. A major part of the task of the Physical Damage Division in Japan was the determination of the effectiveness of high-explosive bombs against Japanese industrial targets. Although this determination was not accomplished completely, a substantial addition was made to the body of data relating size, type, and fusing of high-explosive bombs to the damage suffered by certain building types.

2. Two major factors contributed materially to the success of the Division in accomplishing this purpose. One of these was the bombing policy of the Twentieth AF, that of attacking Japanese cities with incendiary bombs and industrial targets with high-explosive bombs; the other was the fact that it was generally not necessary to attack a target repeatedly. The latter situation left a number of relatively "clean" targets and made them comparatively easy to analyze, a condition found but rarely in Germany.

3. The factors, mostly tactical, affecting the Twentieth AF bombing policy are discussed below. Characteristics of bombs, fuzes and targets relevant to weapon effectiveness are also discussed. The mean area of effectiveness, abbreviated MAE, as a measure of comparative effectiveness of bombs is discussed. Numerical values of the MAE's for various bombs and building types have been calculated from the field measurements presented in the team reports of the Physical Damage Division. The MAE's given include values for the following: 10,000- and

4,000-pound, light case, and 2,000-, 1,000- and 500-pound, general purpose, high-explosive bombs. These observed MAE's were tested for significance and found reasonably reliable.

B. TWO MAJOR FACTORS AFFECTING THE SUCCESS OF [redacted] WEAPON-EFFECTIVENESS STUDIES

1. Two factors had a major effect on the weapon-effectiveness studies of the Physical Damage Division in Japan. These were the bombing policy of the Twentieth AF and the reaction of the Japanese to AAF bombing of their industrial plants.

a. Weapon Selection Policy of the Twentieth AF. The policy of the XXI Bomber Command (later designated the Twentieth AF) which operated against the Japanese home islands from bases in the Marianas was, generally, to attack the highly congested and highly combustible sections of Japanese cities with incendiary bombs, and to attack industrial targets (often referred to by the Twentieth AF as "precision HE targets") with high-explosive bombs. This policy was adopted despite the facts demonstrated by the Eighth AF bombing of Germany that incendiary bombs were more effective than high-explosive bombs, ton for ton, against many industrial targets, and that attacks using both high-explosives and incendiaries were more effective against most industrial targets. This plan was not adopted blindly, however, and, as a part of the backdrop against which weapon effectiveness in Japan may be advantageously viewed, some of the factors dictating the policy are presented herewith:

(1) Prior to 9 March 1945 the factors governing the decision not to use both high explosives and incendiaries in a single attack against an industrial plant were largely operational. Bombing had been by daylight and at the very high altitudes for which the B-29 had been designed. The differences between the ballistics of the high explosive and those of the incendiary were such as to preclude the practicability of hitting an industrial target with both when they were dropped by a single airplane or formation of airplanes. This fact was particularly true at the bombing altitudes of some 30,000 feet then in use. The condition was not helped by the extreme winds often occurring at these altitudes where velocities up to 200 miles per hour were reported. The one incendiary not seriously affected was the AN-M76, a 500-pound, oil-gel bomb closely approximating the 500-pound, general-purpose bomb in ballistics. These two bombs were used together, being dropped from the same airplane on a number of attacks, but it was felt that such large incendiaries were inefficient and that multiple hits with smaller "packages" of incendiary mix would be far more effective.

(2) The possibility of using both high explosives and incendiaries in a single attack against an industrial

target but dropping them from different formations passing over the target at close time intervals was considered and discarded. To conserve gasoline and allow heavier bomb loads, cruise control procedures required flying singly on the long over-water flight, with assembly just off the coast of Japan for attack in column of formations; following the attack, the return to base was accomplished by planes singly. The assembly procedure proved very difficult, so much so that it was not unusual for airplanes to assemble with the wrong wing, and rarely did a formation actually attack precisely as briefed. Indeed an airplane commander was under orders to attach his plane to some formation, and under no cirumstances to attack alone (this discussion refers to day-light attacks only since formation flying at night was not necessary and was not attempted). Thus, had an attempt been made to attack a target with some formations carrying high explosives and some carrying incendiaries, the probable result would have been that each formation would have dropped both, an undesirable consequence as discussed above.

(3) Following 9 March 1945 other factors affecting bombing policy were added to the purely operational ones. Bombing altitudes were lowered in general to 15,000 to

20,000 feet by day and 5,000 to 12,000 feet by night. Gasoline consumption was lowered, and bomb loads increased. Logistics of bomb supply became a major factor; a minor one was the decision of the Command to plan a few "controlled attacks".

(4) Beginning with the 9 March attack on Tokyo and continuing almost to the end of the war all available incendiary bombs were needed for the night attacks on cities. In fact, in the last attack of each of the first two series of low-level, night, fire attacks the variety of incendiaries used furnished evidence that the bottom of the barrel was being scraped.

(5) In May the XXI Bomber Command decided to carry out a few "controlled attacks", attacks designed to control as many as possible of the variables affecting weapon effectiveness so that analysis of the resulting damage would reveal a maximum of information regarding the effectiveness of certain bomb-fuze combinations for which combat data were scarce. The attacks, particularly those in which 4,000-pound, light-case and 2,000-pound, general-purpose bombs were used, proved to be both interesting and fruitful for the Physical Damage Division. Thus, the pattern of Twentieth AF bombing developed so that incendiaries were used for night, urban-area attacks and high explosives

were used largely for daylight attacks against "precision" industrial targets. Notable exceptions were the night radar missions against oil targets by the 315th Wing using high-explosive bombs (500-pound, general purpose, except in one attack where 250-pound and 100-pound, general-purpose bombs were used).

b. Reaction of Japanese to Industrial Bombings. In Europe many of the targets had been hit a number of times by both the USAAF and the RAF with several different bomb-fuze combinations. These successive attacks resulted from the persistent repair policy of the Germans and the duration of the air war. They rendered analysis of weapon effectiveness extremely difficult, often impossible. In contrast, the relatively short duration of the strategic bombing campaign against Japan, the lack of a repair policy, and the decision of the Japanese to abandon plants and disperse their industry, often after a single attack, left comparatively "clean" targets. Many of them had been hit with a single bomb-fuze combination, and, in a number of cases, it was possible to isolate the effects of a single bomb with reasonable certainty. As a result, valuable additions to the data of effectiveness of high-explosive bombs have been obtained, subject of course to the usual vagaries of such data: wide variation from incident to incident, and insufficient sample size.

C. FACTORS AFFECTING WEAPON EFFECTIVENESS

1. The primary purpose of bombing is to damage the enemy; in the strategic bombing of industrial targets the specific purpose is to stop

production for the maximum period of time possible. The latter can be accomplished most efficiently by exploding bombs at the exact spots where they will have the maximum damaging effects on the particular type of target under attack; however, just enough (and no more) bombs should be used to cause sufficient damage to accomplish the desired result. If production in the plant be restored to a certain critical point, which depends on the particular industry as a whole and on the enemy's entire war economy, then and only then must the target be re-attacked. A number of uncertainties involved in executing an ideal attack, as described above, render difficult such an accomplishment. Many obvious ones and some not so obvious, principally those of an operational nature, may be dismissed without discussion. Others, however, such as the damaging characteristics of the bomb, the functioning of the fuze and its reliability, the characteristics of the target and its vulnerability -- major components of the field of terminal ballistics about which relatively little reliable knowledge exists -- are of such importance to an understanding of the limitations and results of weapon-effectiveness analysis that they are discussed below.

a. Damaging Characteristics of Bombs. Progress has been made by the services, and, during the war, by civilian research, both in this country and in England, in establishing the mechanics of the explosion of a bomb. For specific bombs, magnitude and duration of blast pressure; number, sizes, and velocity of fragments; and velocity and acceleration of the shock wave through certain media have been established with fair reliability. Likewise, the magnitude and direction

of the striking velocity of most of the U. S. bombs when dropped from different altitudes at various flying speeds are known. Test data exist which relate these factors to the physical characteristics of the target, such as the effect of blast pressure on brick walls or on glass windows, and the effect of earth shock on reinforced-concrete slabs, but the information at best is meager. Data from full-scale tests made by exploding bombs in buildings are practically nonexistent.

b. Fuzing Considerations. Fuzes are manufactured to close tolerances; the mechanics of activation and the time required for detonation are both reliably known. But little has been done to determine the relationship between these quantities and the various types of roof covering likely to be encountered in targets. Although it seems self-evident that light, fragile, asbestos-cement roofing is incapable of reducing the momentum of a bomb traveling at 900 feet per second sufficiently to activate the inertia tail fuze, it was not until 1944 that contact nose fuzes with delays shorter than 0.1 second were available in quantity. Prior to that time, therefore, the choice of fuze with respect to delay was between those with practically no delay and others with relatively long delays. This meant then, where roofing offered almost no resistance or where roofing had been removed by earlier attacks, that the bomb had perforce to be exploded (1) either instantaneously (that is, the bomb would have traveled only a foot or two after impact) or (2) after it had had time to bury itself under the floor of the building, assuming normal, single-story, industrial construction. The latter case might or might not be

desirable, depending upon the vulnerability of the target.

c. Target Vulnerability. Although it was generally accepted that the best way to stop production was to damage the machine tools in the production line, there was disagreement among ordnance officers, target analysts, and others concerned with the problem as to how to accomplish it. Could debris from the damaged structure be relied upon to accomplish the desired damage to machines? Could fragments be relied upon or should the bombs be exploded beneath the floor and reliance be placed upon earth shock. Test data were scarce, only relatively small useful examples having been obtained from the British experience under German attack. Great reliance had to be placed upon photo interpretation of attacks on enemy targets. Serious limitations soon developed: (1) accurate determination of the number of bombs causing the damage and of their points of detonation was difficult; and (2) the relation between visible damage to the structure, which could be measured with fair consistency, and damage to machinery and production, which could not be seen in aerial photographs, was uncertain.

2. Difficulties of Field Survey. It was thought that many of the doubts and disagreements might be resolved by ground surveys of captured enemy targets. But it soon became evident to field teams that many difficulties confronted them also. To determine with certainty the size and type of bomb and its exact point of detonation was not easy. Cross-checking field data with Air Force records was a tedious job, and was subject to error. Limitations of time and of qualified personnel permitted examination of only a small proportion of the damaged

targets. The field teams were forced, as the photo interpreters had been, to limit the sub-classification of building types in order to preserve data samples of significant size. For the sake of consistency the classifications adopted were those previously used by the Joint Target Group, which had been derived from the earlier work in England of the RES Section, Research and Experiments Department, Ministry of Home Security. Table ~~I~~ 1 which follows gives these classifications together with definitions of damage categories, vulnerability, and fire classifications.

3. Scope of Japanese Survey.

a. Thus limited, the Physical Damage Division chose its high-explosive targets with the purpose of obtaining the maximum of information regarding the effectiveness of ~~these~~ bombs and fuzes for which the least data existed. A special effort was made to isolate and measure the effects of individual bomb hits where possible.

b. A total of 59,989 tons of high-explosive bombs was reported dropped on Japan. The Physical Damage Division surveyed 20 targets which had been attacked with about 6,500 tons of high-explosive bombs. Field teams plotted in these target areas about 1,358 tons of bombs, including only the following bombs (weights in pounds): 10,000, 4,000, 2,000, 1,000, and 500. Table ~~II~~ 2 gives the number and size of bomb and also the type of target.

TABLE 1

TYPES OF DAMAGE

Damage to Buildings, Industrial and Domestic

a. Structural: damage to principal load-carrying members (trusses, beams, columns, load-bearing walls, floor slabs in multi-story buildings) requiring replacement or external support during repairs. Light members such as purlins and rafters are not included.

b. Superficial: damage to purlins and other light members: stripping of roofing and non-load-bearing exterior walls. Damage to glass and interior partitions not included.

Damage to Machinery, Utilities and Equipment

a. Total: not worth repair.

b. Heavy: requiring repair beyond capacity of normal maintenance staff: usually returned to manufacturer.

c. Slight: requiring repair within capacity of normal maintenance staff.

Damage to Contents Other than Machinery and Equipment

a. Total: not usable

b. Other: usable if reprocessed or repaired.

BUILDING TYPES OR CLASSIFICATIONS

(Tables A and B from Joint Target Group)

TABLE A

GROUP		TYPE SYMBOL	DESCRIPTION
A. Single-story, no traveling cranes, spans generally less than 75 ft, heights at eaves generally less than 25 ft, area of 10,000 sq ft or more	1. With saw-tooth roofs	A1.1	All buildings of this group with saw-tooth roofs other than those included in Types A1.2, A1.3, and A1.4
		A1.2	Frame and roof slab of monolithic reinforced concrete
		A1.3	Exposed top chords of trusses
		A1.4	Stressed-skin type of reinforced concrete (e.g. Zeiss Dywidag)

GROUP		TYPE SYMBOL	DESCRIPTION
	2. Without saw-tooth roofs	A2.1	Simple beam and column
		A2.2	Arches and rigid frames
		A2.3	Truss construction
		A2.4	Frame and roof slab of monolithic reinforced concrete
		A2.5	Stressed-skin type including concrete shell
B. Single-story with traveling cranes; any length of span; area of 10,000 sq ft or more	1. Bldgs housing heavy cranes	B1	Buildings containing runways for heavy cranes (capacity 25 tons or more); height at eaves generally more than 30 ft.
	2. Bldgs housing light cranes	B2	All buildings in this group other than those in B1
C. Single-story; no traveling crane runways; spans greater than 75 ft; height at eaves generally greater than 25 ft; area of 10,000 sq ft or more	1. Main frame members in two directions	C1.1	Roof trusses supported along one side of building by long span trusses and along other side by columns. Permits large door along one side and at ends
		C1.2	Continuous trusses in one or two directions; long span in one direction, supported by columns or exterior walls and by internal columns.
		C1.3	Exposed chord saw-tooth roof buildings; exposed chord trusses supporting major size trusses at 90°. One or both truss systems may be of long span.
		C1.4	Diamond mesh arch.
	2. Main frame members in one direction only	C2.1	Long-span arches, individually supported along sides of building. May be arranged

GROUP		TYPE SYMBOL	DESCRIPTION
			in multiple spans joined along side.
		C2.2	Long-span, triangular or bowstring trusses, individually supported by columns at sides of building. May be arranged in multiple spans joined along side, using common columns. Roof pitch exceeds 2 in 10.
		C2.3	Long-span trusses, top cord of pitch 2 in 10 or less, including exposed cord saw-tooth roofs, individually supported by columns along sides of building. May be arranged in multiple spans using common columns or may be continuous over internal columns.
	3. Shell-type construction	C3	Stressed-skin including concrete shell construction.
D. All single-story buildings of less than 10,000 sq ft plan area		D	This type covers all single-story industrial buildings, regardless of type of construction if under 10,000 sq ft in plan area.
E. Multi-story frame buildings.		E1	Earthquake-resistant; extremely heavy steel or reinforced-concrete, multi-story construction, designed to resist heavy lateral loads.
		E2	Structures in this group other than those in E1

GROUP		TYPE SYMBOL	DESCRIPTION
F. Multi-story, wall-bearing buildings. (May have internal columns.)		F1	Earthquake-resistant, wall-bearing construction. (Walls of reinforced brick, concrete, or very massive masonry.)
		F2	Structures in this group other than those in F1.
S. Special Structures		S	Coke ovens, test cells, fuel storage, boilers in power plants, etc.

HE VULNERABILITY CLASSES

TABLE B

HE Vulnerability Class	Substructural Groups (Symbols refer to Table A)
V1	E1
V2	B1, B2
V3	E2, F1
V3A	F2
V4	A1.1, A1.2, A1.3, A2.1, A2.2, A2.3, A2.4, D
V4A	C1.2, C1.3, C1.4, C2.3
V5	A1.4, A2.5 C1.1 C2.1, C2.2 C3

FIRE CLASSIFICATION - BUILDINGS AND CONTENTS

C - Combustible: Buildings whose roofs and/or walls are constructed of combustible material. The floors (except the ground floor) are required to be of similar construction. Wood-frame buildings with noncombustible sheeting on roof and/or walls are also included in "combustible" class.

N - Noncombustible: Buildings which have no significant amount of combustible material in the structure, but whose structure is susceptible to damage by fire in the contents. An example of this type is a building with exposed steel members which may be warped irreparably by the heat of a fire. Roofs of this type are: Corrugated asbestos, corrugated iron, pre-cast or pour-in-place cement or gypsum on exposed steel, and reinforced concrete 2 1/2-inches thick or less.

R - Fire-resistive: Buildings which have no significant amount of combustible material in the structure and which will withstand all but the most intense fire without structural damage. Roofs and floors (other than ground) should be of concrete more than 2 1/2-inches thick, and the steel frame should be protected and not subject to ordinary fire damage.

C & N, N & R or C & R used where above types are combined in a single fire division.

TABLE 2

HE BOMBS SURVEYED

Bomb size (pounds)	Type of target	Number of targets	Number of bombs surveyed
10,000 LC	Industrial	7	7
	Urban	2	3
4,000 LC	Aircraft Industry	2	50
	Other Industrial	2	124
	Petroleum	1	12
2,000 GP	Aircraft Industry	3	76
	Other Industrial	2	288
	Petroleum	1	1
1,000 GP	Aircraft Industry	2	744
	Other Industrial	1	143
500 GP	Aircraft Industry	1	28
	Other Industrial	1	30
	Petroleum	1	145
	Total Bombs		1,651
	Total Tons		1,358

c. It should be noted that the Physical Damage Division field teams surveyed only about 2 per cent of the total tonnage of high-explosive bombs reported dropped on Japan.

4. Procedure of Field Survey. At some of the targets it was possible to plot all of the bombs that had hit within the target areas with reasonable certainty; at others this procedure was quite impossible because of the Japanese effort to clean up the area and to begin repairs. In the latter cases only those buildings or incidents promising reliable results were surveyed. Japanese plant officials were interrogated wherever possible and were required to furnish detailed plans of buildings and installations as well as plots showing bomb locations and damage.

If the reliability of these could not be affirmed, plots and plans were prepared by team members. Data relative to casualties, value of damage in yen, estimates of repair time, and loss of production were obtained.

a. Bombs Surveyed.

(1) The 10,000-pound Bomb: light-case (3/8 inch thick), 51 per cent charge-weight ratio, instantaneously fuzed. The use of this light-case bomb was experimental in nature, and it was employed against available targets where very high blast effect was thought desirable. The low charge-weight ratio is due to a very heavy nose section.

(2) The 4,000-pound Bomb: light-case (3/8 inch thick), 80 per cent charge-weight ratio, instantaneously fuzed. It was generally used against light structures where its high blast effect had maximum opportunity to cause widespread damage.

(3) The 2,000-, 1,000- and 500-pound, General-Purpose Bombs: charge-weight ratio 50 to 55 per cent, case thickness 0.30 ~~½~~ inch for 2,000- and 1,000-pound sizes, 0.30 inch for 500-pound bomb. These bombs could be fuzed instantaneously or with various delays. Their uses and effects were more general, and were similar for the three sizes, varying in degree with their respective weights. They could be used to penetrate or to produce heavy fragmentation which was not possible with the

light-case bombs. Fuzed instantaneously or with short delay, they could also be used as blast bombs.

(4) Fuzings. The following fuzings were available for use with high-explosive bombs:

NOSE	TAIL
Instantaneous	Non-delay
0.01-second delay	0.01 second delay
0.025 " "	0.025 " "
0.1 " "	0.1 " "
4 - 5 " "	4 - 5 " "
8 - 11 " "	8 - 11 " "
1 - 144 hour "	1 - 144 hour "

The last three were used infrequently against Japanese targets and were not studied by the Physical Damage Division.

b. Damage to buildings, machine tools, utilities, stores, and the like, was measured and recorded. Only high-explosive damage to buildings will be discussed here. Building damage was classified in two categories, structural and superficial, using the definitions of the Joint Target Group (Table 1).

5. Results of Survey. The field team reports have been examined and the material pertinent to analysis of effectiveness of weapons against buildings has been abstracted and listed in Table 3. From these data gathered from 20 industrial targets, mean areas of effectiveness (MAE) against various building types have been computed for the

five types of bomb listed above. They also are listed in Table 3 together with the method by which each was calculated. These MAE's are shown again in Table 4, together with information on bomb size and fusing, and building type, for ease of analysis. The MAE is a mathematical concept undoubtedly familiar to many readers but for the benefit of the tyro may be described as follows: The area within which all existing target units of a prescribed class will, on the average, be damaged to a prescribed degree by a prescribed weapon. The MAE is discussed at greater length below.

b. Attention is called to the small number of bombs contributing to many of the calculated MAE's, as shown in both Tables 3 and 4. The danger of placing reliance upon most of the values shown will be apparent. It should also be pointed out that the MAE's for the 4,000- and 10,000-pound LC bombs were based upon "structural damage" which included mass distortion of the building frame. This was due to the horizontal loadings distributed over wide areas which were caused by these bombs exploding at roof level. Since this effect was peculiar to the LC bombs and since removal of the roof trusses and supporting columns before resumption of production in the buildings might not have been required, it is possible that comparisons based upon these values may be somewhat biased in favor of the LC bombs. This is particularly true of the light, steel-frame buildings in the A1.1, A2.2, and A2.3 categories (Table 1) in which a considerable portion of the recorded "structural damage" was of this nature.

TABLE III

500-lb GP, 1,000-lb GP, 2,000-lb GP, 4,000-lbLC

HE BOMB DAMAGE DATA & CALCULATED MAE VALUES
FOR 20 INDUSTRIAL TARGETS IN JAPAN

Report Number	Target Name & Location	Building Data (Damaged Buildings Only) Structure Type (JTG)	Material	Number of Floors	Number of Buildings Structurally Damaged	Area of Building Plan	Floor	Areas in 1,000's Sq. Feet Area of Structural Damage Roof	Floor	Fraction of Roof Damaged	Area of Superficial Damage	Weight (Pounds)	Bomb Data Type	Number	DH	NM	C	No C	Fuzing (Seconds) Tail	Nose	Tons	Density on Building Area Plus NM Area (Tons/Acre)	Structural Damage Estimates (1,000's of Sq. Feet/Ton) Average Area of Damage (Total Area of Structural Damage ÷ Tons of Bombs)	MAE Binomial Method	Annular Ring Method	Average Circle Method	Remarks
107	2nd Naval Fuel Depot Yokkaichi	D	RC	1	1	7.3	7.3	0.1	0	.01	0	500	GP	1	1	0	0	1	ND	0.025	0.25		0.4			0.5	
115	Konan Plant, Kawanishi Aircraft	B2	Steel	1	3	208.0	208.0	39.4	0	.19	170			17	17	0	4	13	ND	0.01	4.25	.83	9.3	11.2			Ave Isolated Damage
		B2	Steel	1	2	--	--	27.4	0	--	255			9	9	0	1	8	ND	0.01	2.25	--	12.2	12.2			Each Bomb
Mem.	Sumitomo Metal Co., Nagoya Lt Alloy Plant	B2	Steel	1	3	250.8	250.8	30.7	0	.12	132	500	GP	28	23	5	12	16	ND	0.025	7.0		4.4	5.7			Exponential Method
106	Funakata Plant, Aichi Clock & Elec Co.Ltd At Nagoya,	A1.1	Steel	1	2	73.1	73.1	8.6	0	.12	3	1000	GP	2	2	0	0	2	ND	0.01	1		8.6			14.1	
		B2	Steel	1	1	22.0	22.0	3.2	0	.15	6			1	1	0	0	1			0.5		6.4			20.0	
		D	Steel	1	1	8.6	8.6	1.7	0	.20	-			1	0	1	0	1			0.5		3.4			24.6	
		E2	Steel	2	1	10.1	20.2	1.6	1.6	.16	-			1	0	1	0	1			0.5		6.4			11.4	
109	Kawanishi Aircraft Plt. Takarazuka	B2	Steel	1	3	279.5	279.5	90.9	0	.33	189			35	24	11	22	13			17.5	2.44	5.2	9.4			Ave Isolated Damage
		B2	Steel	1	1	--	--	12.7	0	-	141			3	3	0	0	3			1.5	--	8.5	8.5			Each Bomb
113	Kawanishi Aircraft Plant Naruo	B2	Steel	1	4	420.1	420.1	128.2	0	.31	291			51	51	0	40	11			25.5	2.46	5.0	7.5			Ave Isolated Damage
		B2	Steel	1	6	--	--	37.4	-	-	-			13	13	0	3	10			6.5	--	5.8	5.8			Each Bomb, Heavy
		E2	RC	3	3	147.4	442.2.	7.4	7.0	.05	140	1000	GP	12	10	2	2	10	ND	0.01	6.0	.72	2.4	3.0			Construction
104	Aichi Eitoku Aircraft Plant, Nagoya	A1.3	Steel	1	2	230.5	232.2	68.0	0	.29	162	2000	GP	4	4	0	4	0	ND	0.01	4.0		17.0			21.8	
		A2.3	Steel	1	2	36.2	36.2	22.2	0	.61	14			4	2	2	2	2			4.0		5.5			26.5	
		E2	Steel	2	1	32.4	64.8	1.8	5.4	.06	27			2	1	1	2	0			2.0		3.6			13.8	
		C1.2	Steel	1	1	178.2	178.2	1.8	0	.01	642			1	1	0	1	0			1.0		1.8			4.1	
		A2.4	RC	1	1	186.0	186.0	0.4	0	.00	0			1	1	0	0	1	ND	0.01	1.0		0.4			0.4	
106	Funakata Plant, Aichi Clock & Elec Co.Ltd At Nagoya	E1	Steel	3	1	9.8	29.3	5.7	1.8	.58	0			1	1	0	0	1	ND	Inst	1.0		7.5			15.5	
107	2nd Naval Fuel Depot Yokkaichi	D	RC	1	1	2.2	2.2	0.4	0	.18	0			1	1	0	0	1	ND	Inst	1.0		0.4			0.4	
119	Nakajima Musashi AC Wks, Tokyo	A1.1	Steel	1	1	146.0	146.0	10.8	0	.07	3			1	1	0	1	0	0.025	0.1	1.0		10.8		22.9		
		E1	RC	5	1	264.0	1284.2	0	21.0	0	-			1	1	0	0	1			1.0		21.0		32.3		
		E2	RC	4	2	388.4	1151.6	20.5	81.7	.05	17			9	7	2	3	6	0.025	0.1	9.0		11.4		28.8		
120	Mitsubishi Heavy Ind - Shizuoka	B2	Steel	1	1	660	660	191	0	.29	-			13	9	4	11	2	0.025	0.025	13.0	.74	14.7	20.4			
-	Hitachi Co, Kaigan Plant	B2	Steel	1	6	785.2	785.2	315.3	0	.40	-			74	61	13	70	4	0.025	0.1 & .025			4.3	8.4			(Information Fr Ships
		B1	Steel	1	1	96.2	96.2	60.2	0	.63	36	2000	GP	11	7	4	10	1	0.025	.025 & 0.1		3.5	5.5	12.4			(Bombardment Gp Survey
105	Aichi-Atsuta AC Engine Plant, Nagoya	A1.1	Steel	1	2	142.5	151.5	44.5	0	.31	90	4000	LC	2	1	1	1	1	ND	Inst	4.0		11.1			21.7	
		D	Wood	1	3	10.9	10.9	8.1	0	.74	0			1	1	0	1	0			2.0		4.0			47.2	
106	Funakata Plant, Aichi Clock & Elec Co.Ltd At Nagoya	A1.1	Steel	1	8	578.4	578.4	229.7	0	.40	280			16	9	7	10	6			32.0		7.2			24.3	
		A2.3	Steel	1	3	81.4	81.4	36.0	0	.44	52			6	0	6	6	0			12.0		3.0			21.3	
		B2	Steel	1	2	36.1	36.1	9.2	0	.25	17			2	1	1	1	1			4.0		2.3			16.9	
		D	Steel	1	1	7.2	7.2	1.4	0	.19	6			1	0	1	0	1			2.0		0.7			15.7	
		E2	Wood	2	1	4.0	8.0	0.8	0	.20	0			1	0	1	1	0			2.0		0.4			155.8	
107	2nd Naval Fuel Depot Yokkaichi	A2.2	Steel	1	2	21.7	21.7	16.5	0	.76	5			2	2	0	1	1			4.0		4.1			19.3	
		D	Steel	1	1	1.8	1.8	1.8	0	1.0	0			1	0	1	1	0			2.0		0.9			7.7	
		D	RC	1	1	2.2	2.2	0.5	0	.23	0			1	0	1	0	1			2.0		0.3			3.6	
		E2	RC	2	1	9.6	19.2	0	1.3	0	0			1	0	1	0	1			2.0		0.7			4.6	
108	Kawasaki AC Co. Akashi	A1.1	Steel	1	7	1094.5	1094.5	135.7	0	.12	552			7	4	3	2	5			14.0		9.7			25.7	
		D	Steel	1	2	12.0	12.0	9.6	0	.80	2			2	0	2	1	1			4.0		2.4			24.5	
		C1.1	Steel	1	1	106.0	106.0	79.8	0	.75	26			1	1	0	1	0			2.0		39.9			45.0	
		A2.3	Steel	1	1	62.5	62.5	39.2	0	.63	12			1	1	0	0	1			2.0		19.6			45.0	
114	Sumitomo Light Metals Ind., Osaka	B2	Steel	1	27	1392.8	1392.8	880.0	0	.63	512	4000	LC	95	71	24	59	36	ND	Inst	190	2.84	4.6	15.4			

JTG - Joint Target Group
DH - Direct Hit
NM - Near Miss
C - Crater
MAE - Mean Area of Effectiveness
NA - Not Available
NC - No Crater

10,000-lb Special LC, Fuzed Instantaneous Nose

TABLE III (Contd)

Report	Target	Building Data (Buildings within Maximum Distance Damage)				Areas in 1000's of Square Feet				Distance to Bomb Damage (In Feet from Point of Detonation)					Structural Damage Estimates (1000's Square Feet/Ton)		
Number	Name and Location	Structure Type (JTG)	Structure Material	Number of Buildings At Risk	Number of Buildings Structurally Damaged	Area of Structural Damage	Area of Risk	Fraction of Building Area Damaged	Area of Superficial Damage	DH or NM Distance	Minimum Distance No Damage	Maximum Distance Damage	Minimum Distance Damage	Maximum Distance Continuous Damage	Continuous Area (Area of Maximum Distance Continuous Damage Circle ÷ 5000	MAE Annular Ring Method (Area of Maximum Distance Damage Circle X Fraction of Building Area Damaged ÷ 5000)	Remarks
101	Toriimatsu Factory Nagoya Arsenal, Nagoya	D	W	5	4	14.2	32.7	0.43	0	340	400	735	340	NA	NA	146.0	
102	Toyoto Motor Co. Ltd Koromo	D	W	14	8	15.9	66.7	0.24	8.5	70	360	510	70	NA	NA	39.2	
		B2	S	6	2	16.7	220.0	0.08	156.1	60	100	-	60	NA	NA	17.5	
103	Takagi Factory, Nagoya Arsenal, Nagoya	A2.1	W	5	2	22.6	147.7	0.15	0	470	470	770	440	NA	NA	55.9	
		D	W	3	3	23.0	23.0	1.00	0	480	NA	620	480	NA	NA	241.5	
		A1.1	S	1	1	37.0	50.0	0.74	0	DH	0	-	0	200	25.1	41.8	
110	Mitsubishi Heavy Ind. Ltd., Kobe	A2.3	S	2	1	2.9	44.5	0.07	36.3	80	NA	-	80	NA	NA	3.7	
111	Kawasaki Locomotive & Car Co., Kobe	B1	S	2	2	56.5	84.6	0.67	17.6	DH	0	360	0	295	54.7	54.5	
122	Sumitomo Chem.Co.Ltd. Light Metal Works at Niihama	B2	S	2	1	22.4	-	-	59.2	DH	0	140	0	140	12.3	7.6	Average Circle Method
		A2.3	S	1	1	5.4	-	-	8.2	175	175	275	180	NA	NA	31.5	Average Circle Method
123	Shimada Urban Area	D	W	34	34	-	-	-	-	-	300	460	60	NA	NA	70.0	Average Circle Method
128	Ube	D	W	21	16	35.0	-	-	9.0	DH	0	-	0	NA	NA	39.2	Bomb #2 on Ube Soda Co.,Av. Circ. Method
		D	W	5	5	-	-	-	-	150	200	-	150	NA	NA	43.8	Bomb #1 on Resident.Dist.,Av. Circ. Method
		D	W	65	23	-	-	-	-	25	200	-	25	NA	NA	41.8	Bomb #3 on Resident.Dist.,Annular Ring Method

TABLE ~~IV~~ 4

Mean Areas of Effectiveness
~~for~~ Of HE Bombs for Structural Damage

Bomb Size	Fusing Tail	Fusing Nose	No of Bombs		Bldg type	(Weighted MAE) (1,000 sq ft/ton)		Remarks
500-lb	ND	0.025	28)	54	B2 Steel	5.7)	8.4	
"	ND	0.01	26)		B2 Steel	11.4)		
"	ND	0.025	1		D.R.C.	0.1		
1000-lb	ND	0.01	2		A1.1 Steel	14.1		
"	ND	0.01	103		B2 Steel	8.1		
"	ND	0.01	1		D Steel	24.6		
"	ND	0.01	1		E2 Steel	11.4		2 floors
"	ND	0.01	12		E2 R.C.	3.0		3 floors
2000-lb	0.025	0.10	1		A1.1 Steel	22.9		
"	ND	0.01	4		A1.3 Steel	21.8		
"	ND	0.01	4		A2.3 Steel	26.5		
"	ND	0.01	1		A2.4 R.C.	0.4		
"	0.025	0.10	11		B1 Steel	12.4		
"	0.025	0.10	74)	87	B2 Steel	8.5)	10.3	
		0.025	)			)		
	0.025	0.025	13)		B2 Steel	20.4)		
"	ND	0.01	1		C12 Steel	4.1		
"	ND	Inst.	1		D.R.C.	0.4		
"	ND	Inst.	1		E1 Steel	15.5		3 floors
"	ND	0.01	2		E2 Steel	13.8		2 floors
"	0.025	0.10	1		E1 R.C.	32.3		5 floors
"	0.025	0.10	9		E2 R.C.	28.8		4 floors

TABLE ~~IV~~ 4 (continued)

Bomb Size	Fusing Tail	Fusing Nose	No of Bombs	Bldg type	(Weighted MAE) (1,000 sq ft/ton)	Remarks
4000-lb	ND	Inst.	25	A1.1 Steel	24.5	
"	ND	Inst.	2	A2.2 Steel	~~38.6~~ 19.3	
"	ND	Inst.	7	A2.3 Steel	24.7	
"	ND	Inst.	97	B2 Steel	15.5	
"	ND	Inst.	1	C1.1 Steel	45.0	
"	ND	Inst.	1	D Wood	31.7	
"	ND	Inst.	4	D Steel	19.5	
"	ND	Inst.	1	D.R.C.	3.6	
"	ND	Inst.	1	E2 R.C.	9.2	2 floors
"	ND	Inst.	1	E2 Wood	155.8	2 floors
10,000-lb		Inst.	1	A1.1 Steel	41.8	
"		Inst.	1	A2.1 Wood	23.5	
"		Inst.	2	A2.3 Steel	17.6	
"		Inst.	1	B1 Steel	54.5	
"		Inst.	2	B2 Steel	12.5	
"		Inst.	7	D Wood	88.8	

D. OBSERVED CHARACTERISTICS OF BOMB DAMAGE

1. The bombs surveyed displayed certain distinct characteristics observable from target to target.

a. The 10,000-pound, light-case bomb, always fuzed instantaneous nose, occasionally made a crater, ~~except in soft soil,~~ but usually exploded on contact with a roof or a floor slab. The damage resulting from this bomb had a characteristic clean-swept appearance near the point of explosion. Small structures, as well as beams, trusses, and columns, were swept away leaving an approximately circular, cleared area with a radius of 30 feet or more (Photos 1 and 2). Structural damage extended over a much greater area, ranging from 25,000 to 60,000 square feet in single-story, steel buildings. The damage was characterized by severe distortion of steel members and occasional spreading collapse (Photos 3 and 4). A locomotive chassis 10 feet from the point of detonation of a 10,000-pound bomb was thrown 75 feet farther away. Another bomb falling in the open caused structural damage to wooden buildings 600 feet distant; a similar one, also falling in the open, failed to cause structural damage to steel buildings 160 feet distant. Occasional heavy, fragment damage occurred; a 6-inch reinforced-concrete wall was pierced by fragments in close pattern at 80 feet (Photo 5). Superficial damage was wide-spread; the areas over which roofs were stripped by single bombs ranged from 36,000 to 156,000 square feet (Photo 3).

b. The 4,000-pound, light-case bomb, always fuzed instantaneous nose, non-delay tail, also exploded upon impact with roof or ground. Craters made by it were shallow and clean swept. This bomb also tended

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By [illegible] NARA, Date 9/3/11

Photo 1. Arrow indicates where 10,000-pound bomb exploded. Building was composite structural steel and reinforced concrete. Note clean-swept surrounding area and superficial damage to building across street.

Photo 2. Arrow shows point of detonation of 10,000-pound bomb. Heavy, steel-frame building was continuous from near side of camera location to remaining section in background. Note clean-swept surrounding area.

by [illegible] NARA, Date 9/3/11

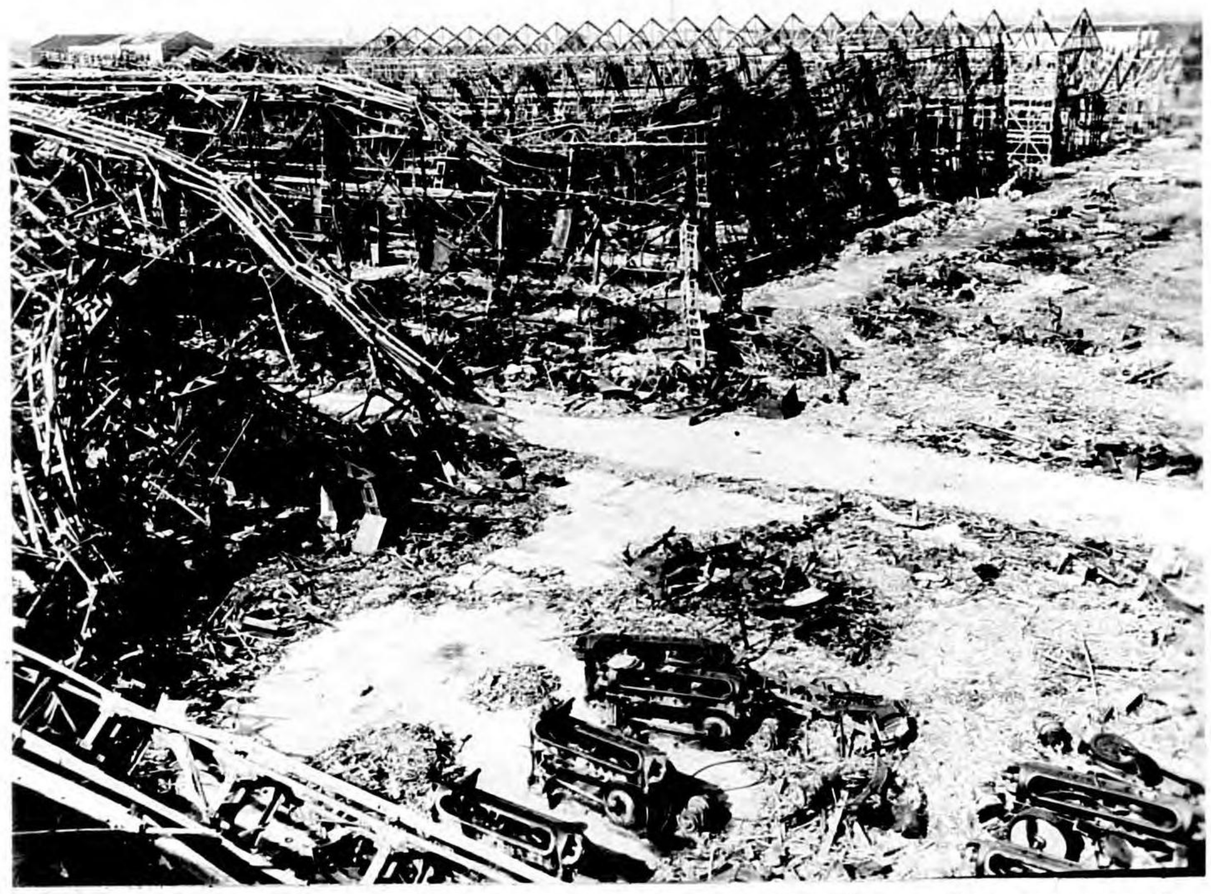

Photo 3. Damage by 10,000-pound bomb: clean-swept area, adjacent distortion, spreading collapse, and widespread superficial damage.

Photo 4. Severe distortion and spreading collapse caused by 10,000-pound bomb.

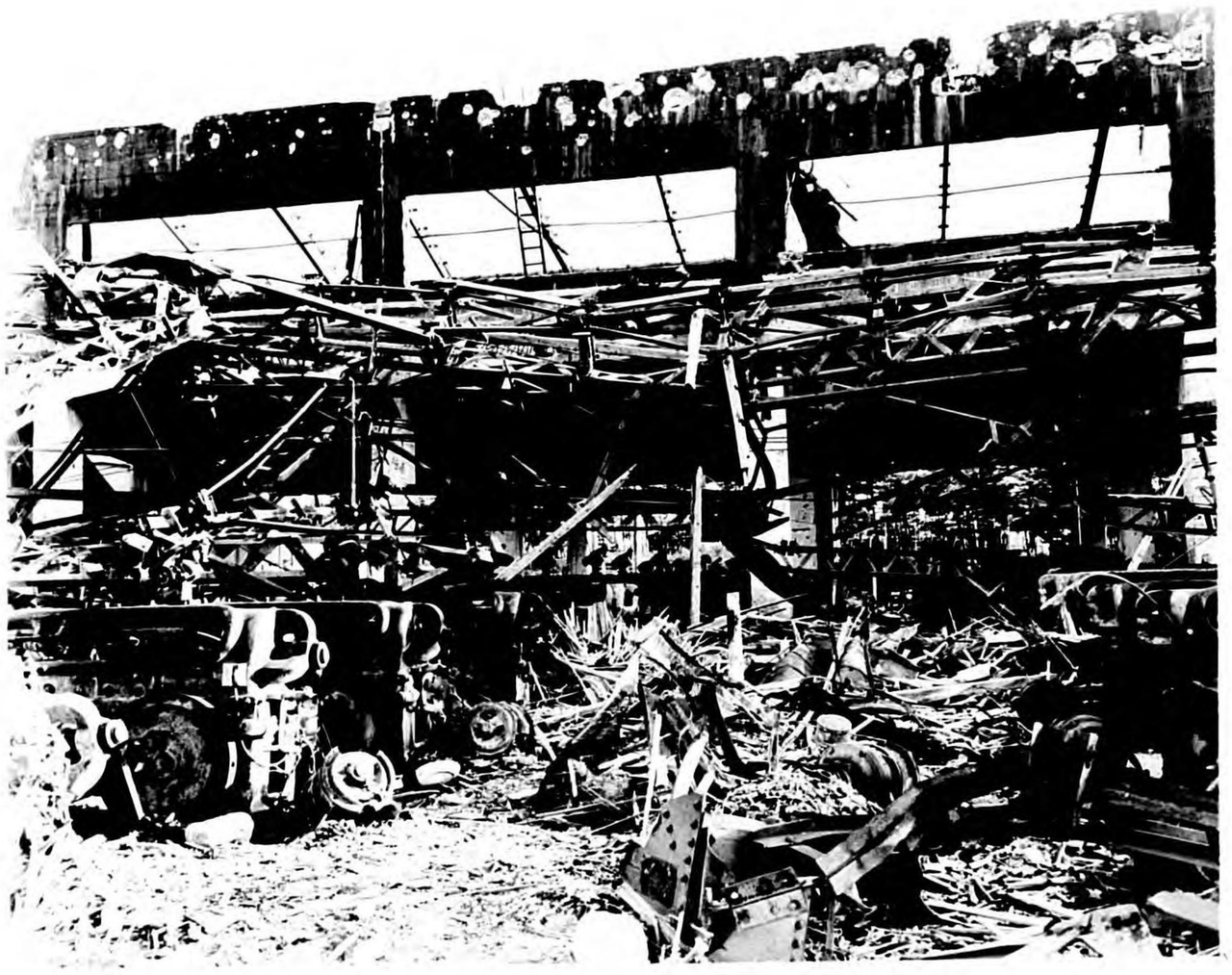

Photo 5. Fragmentation to 6-inch reinforced-concrete wall at 80 feet from 10,000-pound bomb.

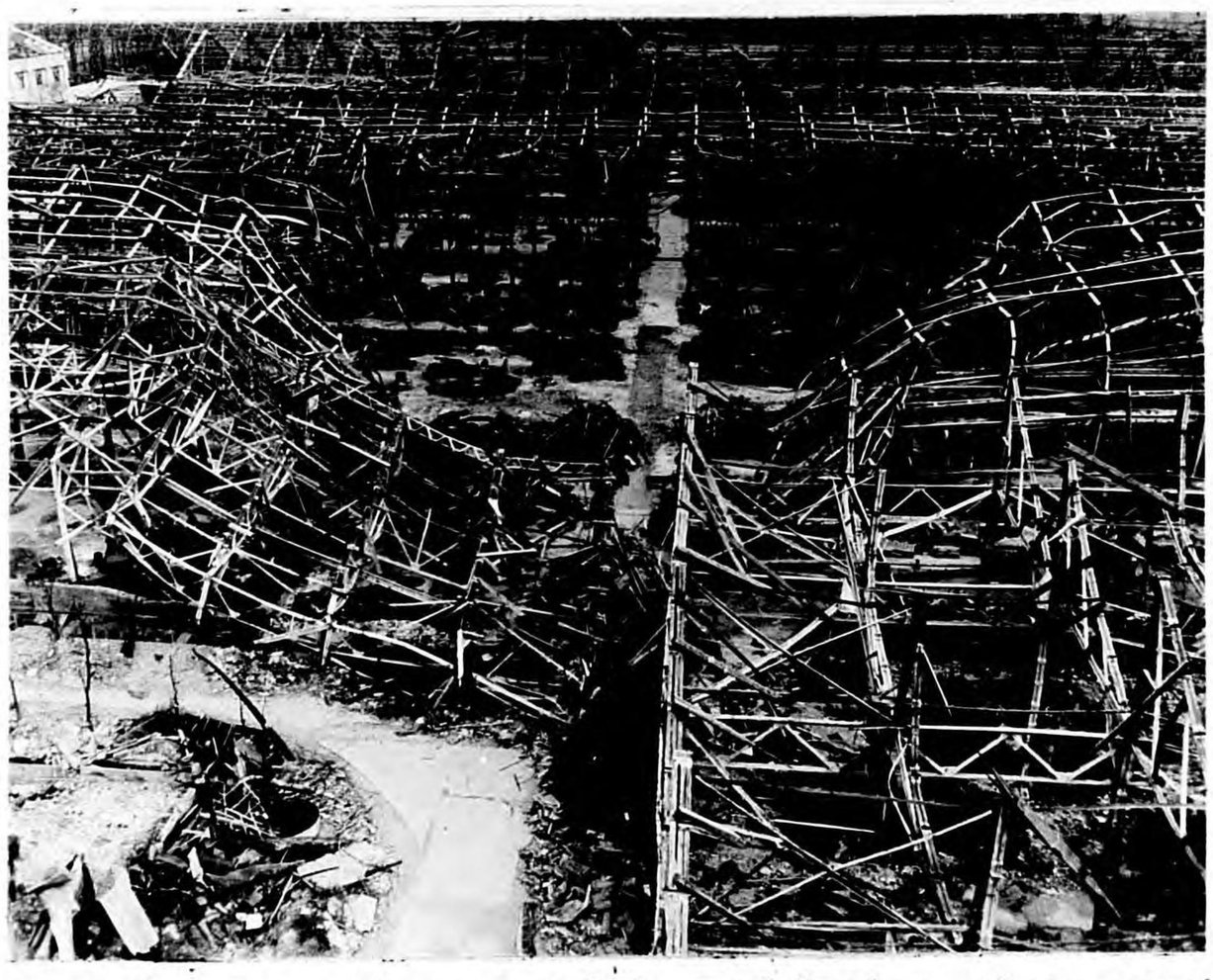

Photo 6. Damage by two 4,000-pound bombs: clean-swept areas, adjacent distortion and collapse, widespread superficial damage.

to sweep clean the area surrounding the point of detonation, almost independently of type of structure, the minimum radius being about 25 feet (Photos 6 and 7). Distortion and spreading collapse often followed (Photos 8 and 9). Single bombs caused structural damage to single-story, steel buildings ranging from 20,000 to 45,000 square feet; there was one case where a single bomb accounted for 80,000 square feet of structural damage to a steel hangar. Heavy, steel-frame buildings with traveling cranes fared little better than those of light, steel framing. The upper floors of multi-story, reinforced-concrete buildings were not immune (Photo 10). The blast pressure from these bombs created high dynamic horizontal loads on building frames which were designed principally for vertical loads (Photo 11). Superficial damage was widespread, the bombs from the first formation often stripping all roofs in the target area (Photos 6 - 11). Consequently, most of the bombs from later formations exploded at floor level. These later bombs averaged considerably less structural damage than the earlier ones -- a point of importance to target analysts.

c. <u>The 2,000-pound, general-purpose bomb</u>, fuzed 0.025-second delay, penetrated well down into multi-story, reinforced-concrete buildings and caused damage to columns and slabs often resulting in the collapse of all floors above (Photos 12 - 15). Over 80,000 square feet of floor area, distributed over three floors and the roof, were damaged by a single bomb. With non-delay tail and either instantaneous or 0.01-second-delay nose fuze, this bomb proved effective against single-story, steel buildings (Photos 16-17). ~~one bomb causing 68,000 square feet~~

Photo 7. Damage by 4,000-pound-bomb near miss: clean-swept area, distortion and spreading collapse, widespread superficial damage.

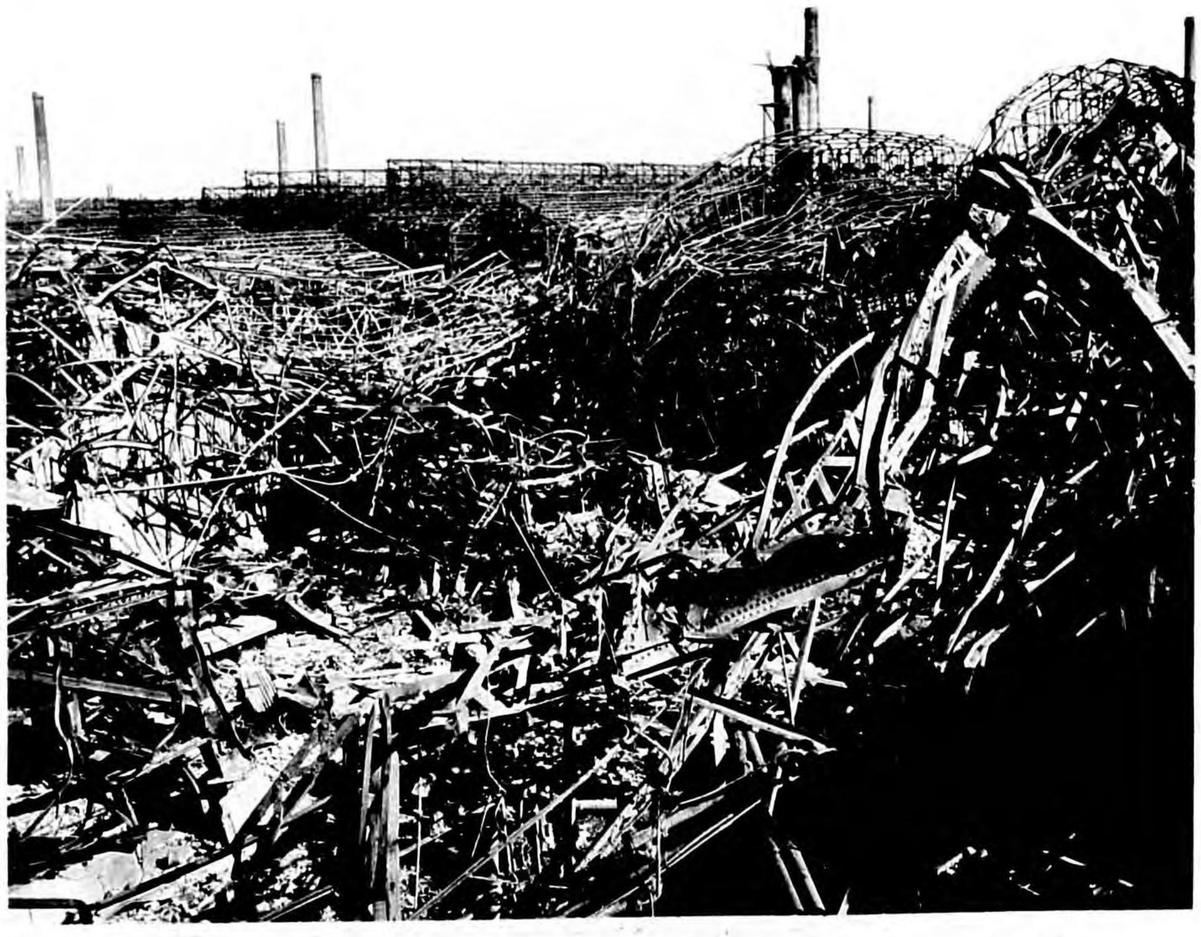

Photo 8. Damage by 4,000-pound bomb. Severe distortion and collapse.

By [illegible] NARA, Date 9/3/71

Photo 9. Damage by two 4,000-pound bombs: severe distortion and collapse, extensive superficial damage.

Photo 10. Damage by 4,000-pound bomb on heavy, reinforced-concrete building.

By [illegible] NARA, Date 9/13/11

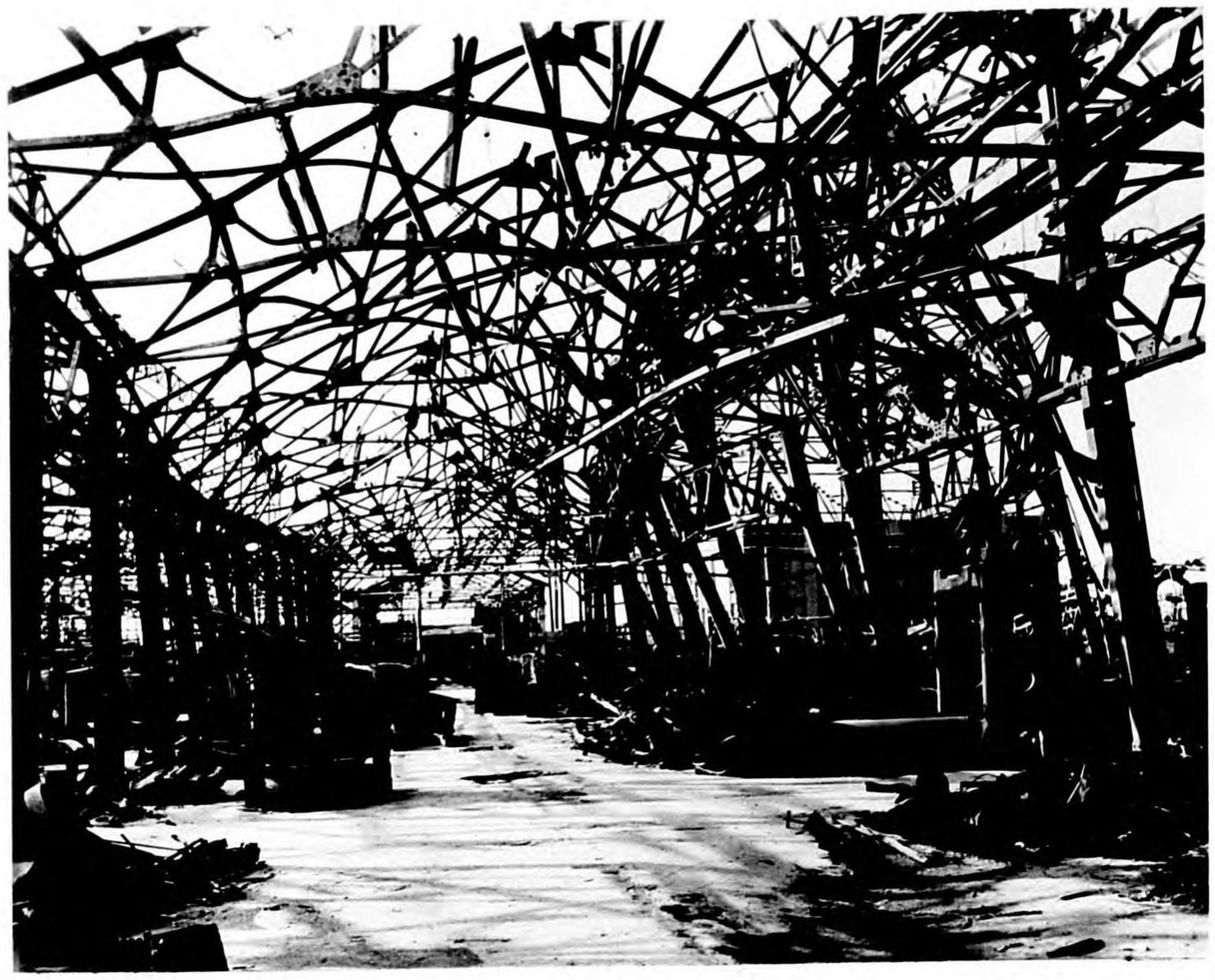

Photo 11. Effect of high dynamic, horizontal loading on sturdy steel frame by 4,000-pound bomb.

Photo 12. Damage by 2,000-pound bomb which perforated roof and exploded well down in building near one corner: entire section of three-story, reinforced-concrete structure brought down.

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Photo 13. Damage by 2,000-pound bomb near miss: two wall columns dropped into crater.

Photo 14. Interior view of incident shown in Photo 13, showing evidence of fire.

Photo 15. Explosion of 2,000-pound bomb below fourth-floor level in four-story, reinforced-concrete building. Damage to third and fourth stories.

Photo 16. Damage by 2,000-pound-bomb direct hit on light, steel-frame, sawtooth-roof building.

~~of structural damage in one instance (Photos 16 and 17).~~

d. The 1,000-pound and the 500-pound, general-purpose bombs, fuzed non-delay tail and 0.01-second delay nose proved equally effective against light, steel-frame buildings, with areas of damage ranging from 5,000 to 20,000 square feet per ton. Five hundred-pound bombs, fuzed non-delay tail, 0.025-second delay nose, were about half as effective against light, steel buildings as those fuzed non-delay tail, 0.01-second delay nose. This estimate is based upon approximately 50 hits, ~~single target (Photo 18)~~. There was less evidence of heavy horizontal loading with these bombs than with the heavier, light-case bombs, and practically no spreading collapse. The effect of the smaller bombs was to punch the roofs full of holes of a fairly uniform size, with little or no distortion beyond, a type of damage comparatively easy to repair (Photos 18-23).

E. METHODS OF ANALYSIS. It became apparent to target analysts early in the war that statistical analysis of comparative effectiveness of bombs was fraught with difficulties. It was conceivable that two identical bombs, fuzed alike and exploded under controlled, static, identical test conditions, would cause comparable areas of damage. The same two bombs dropped during combat into identical buildings would quite probably cause widely differing areas of damage; a ratio of 2 or more was not unusual. Further complications were added by the near miss, the built-upness of target area, and the overlapping of damage areas of two or more bombs. These considerations and others practically precluded the use of average damage as a measure of comparative effectiveness of

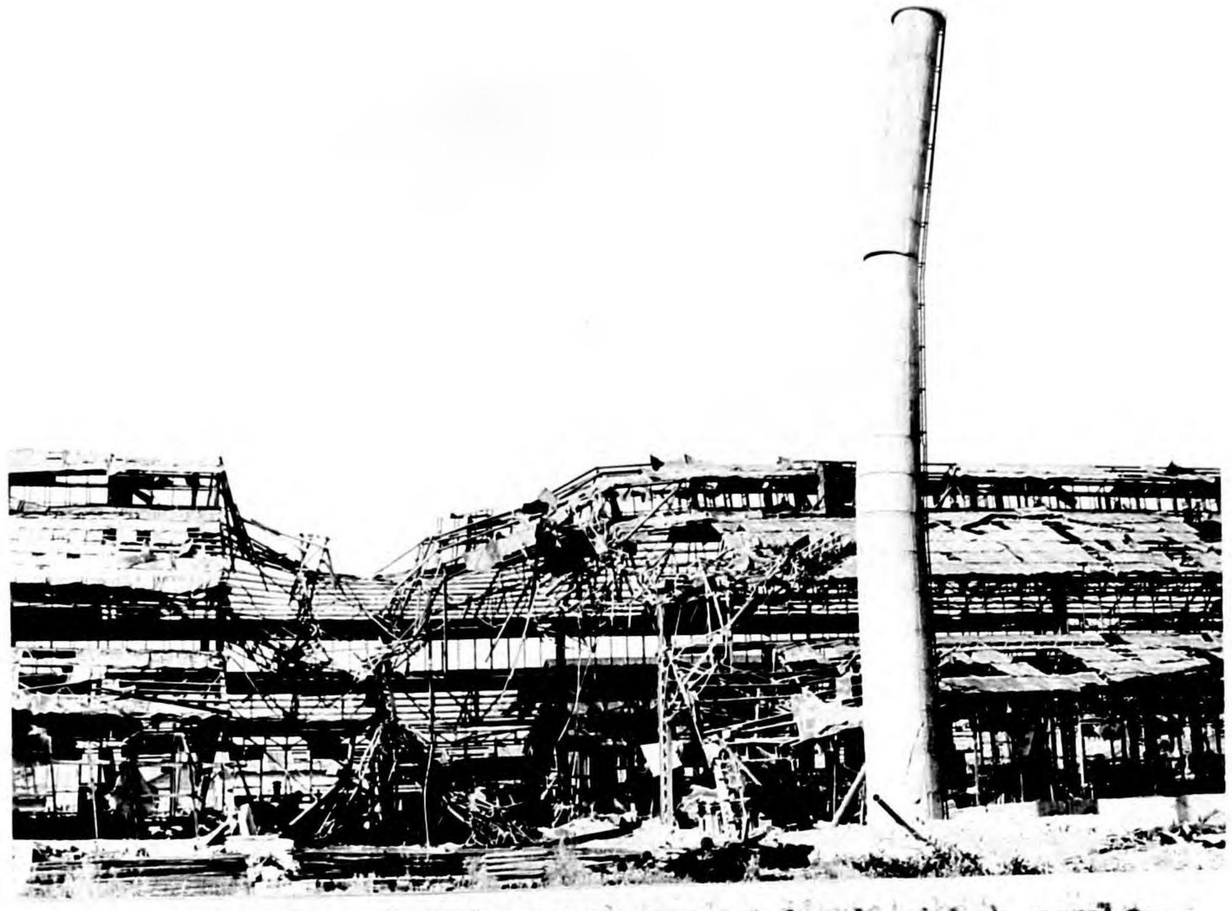


Photo 17. Direct hit of 2,000-pound bomb which exploded below floor level. Steel-frame building with crane runways suffered no spreading damage, but near-miss, earth-shock effect on stack caused shear crack near base at approximately two-thirds of height above base.

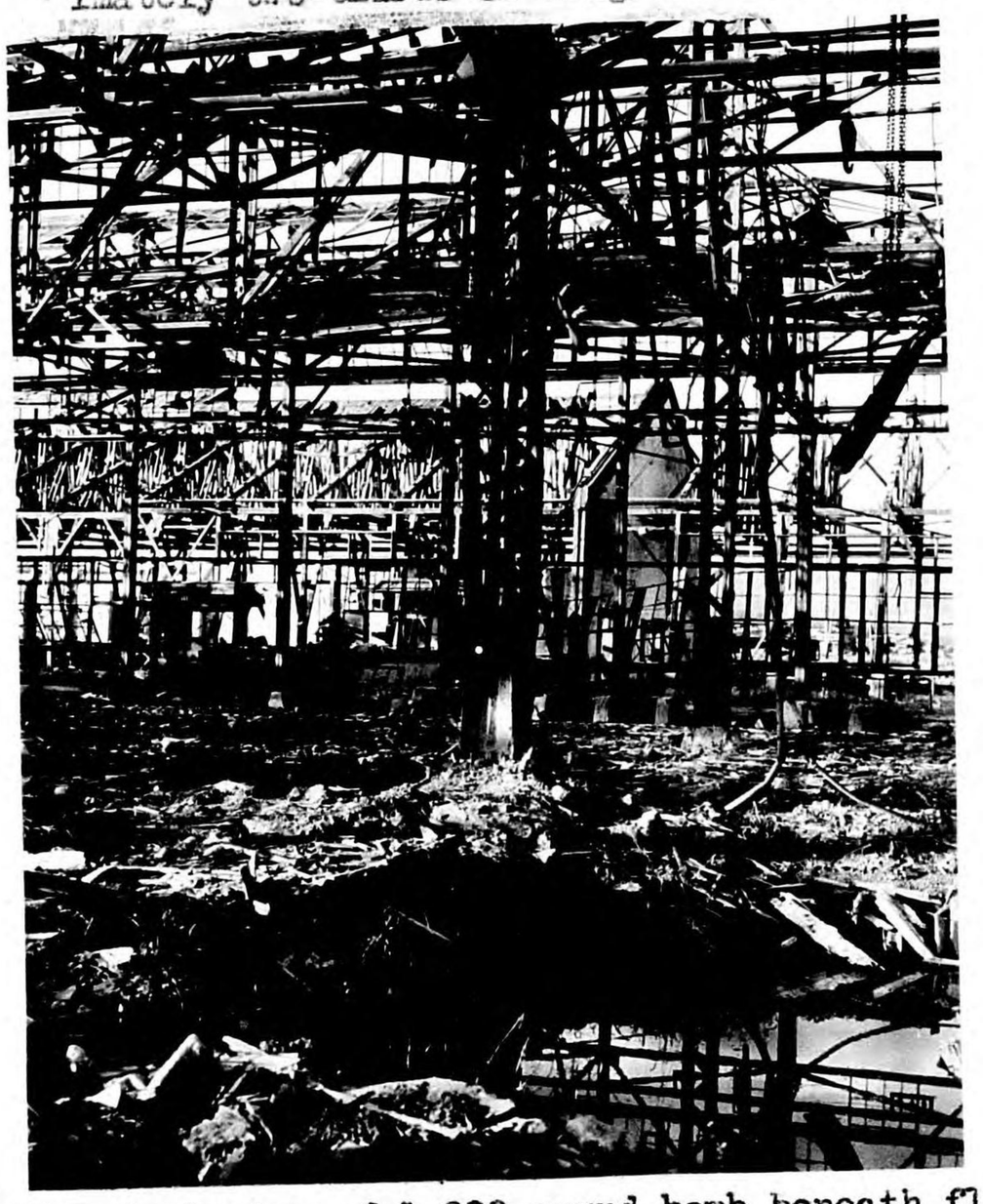


Photo 18. Explosion of 1,000-pound bomb beneath floor caused fragment damage to column in foreground, but no structural damage.

Photo 19. Explosion of 1,000-pound bomb in roof caused limited structural damage and no spreading collapse.

Photo 20. Explosions of 500-pound bombs in roof punched distinct holes, but had no spreading effects.

Photo 21. Explosion of one 1,000-pound bomb in roof punched small hole, but had no spreading effect.

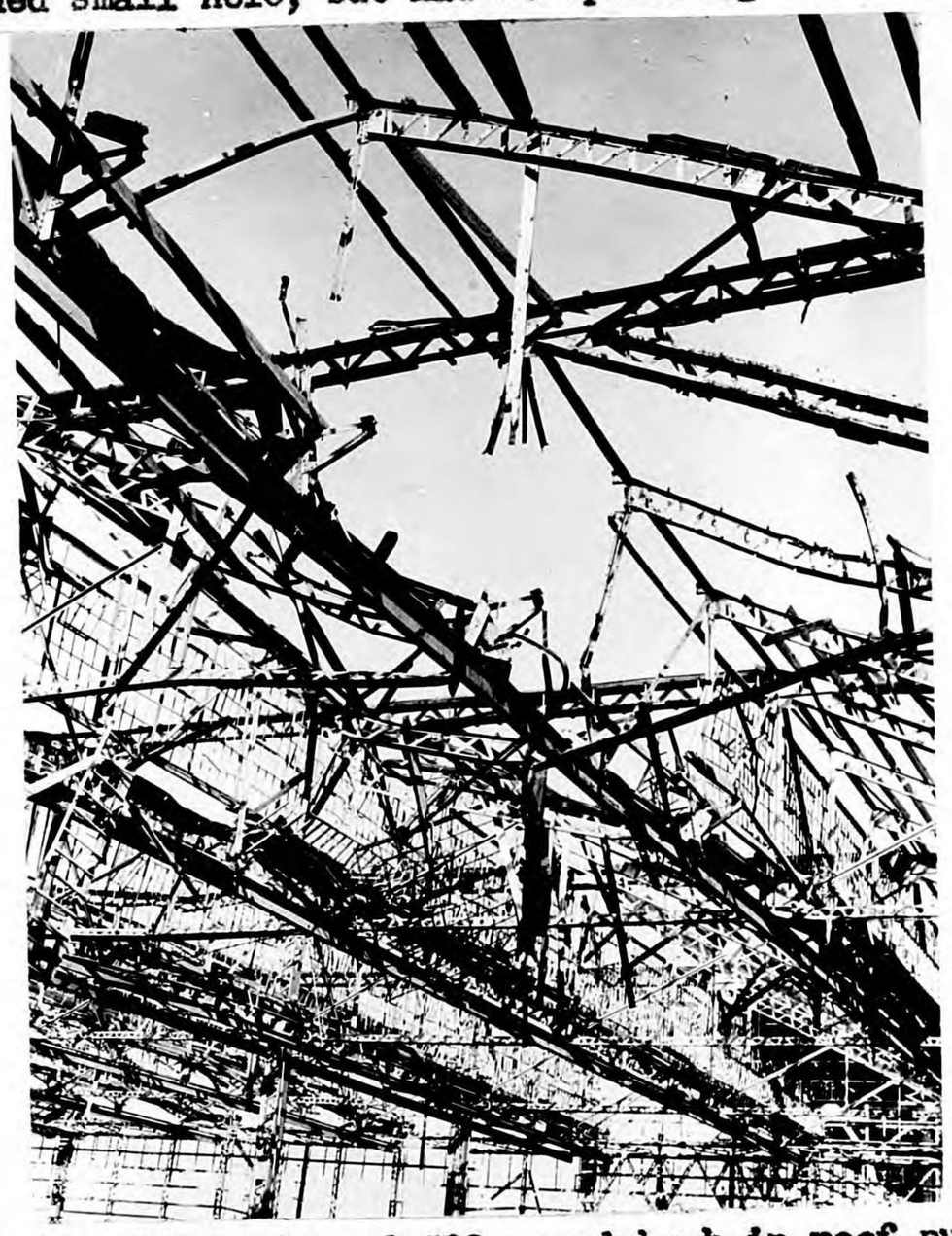


Photo 22. Explosion of 500-pound bomb in roof punched small hole, but heavier members not seriously damaged, and no spreading effect.

Photo 23. Explosion of 500-pound bomb directly above crane made small hole in roof; no spreading effect, and crane virtually undamaged.

different bomb-fuze combinations, or of a single ~~one~~ combination against different types of targets.

2. Inadequacy of Average Damage. The inadequacy of average damage as a measure of comparative effectiveness may be visualized with ease. Assume that two bombs hit a building whose dimensions are large relative to the damaging radius of the bomb; one bomb detonates near the center of the building where its full damaging potential may be realized, and the other near one corner where its potential may not be realized. There have been many such cases in which the ratio of areas of structural damage approximated four.

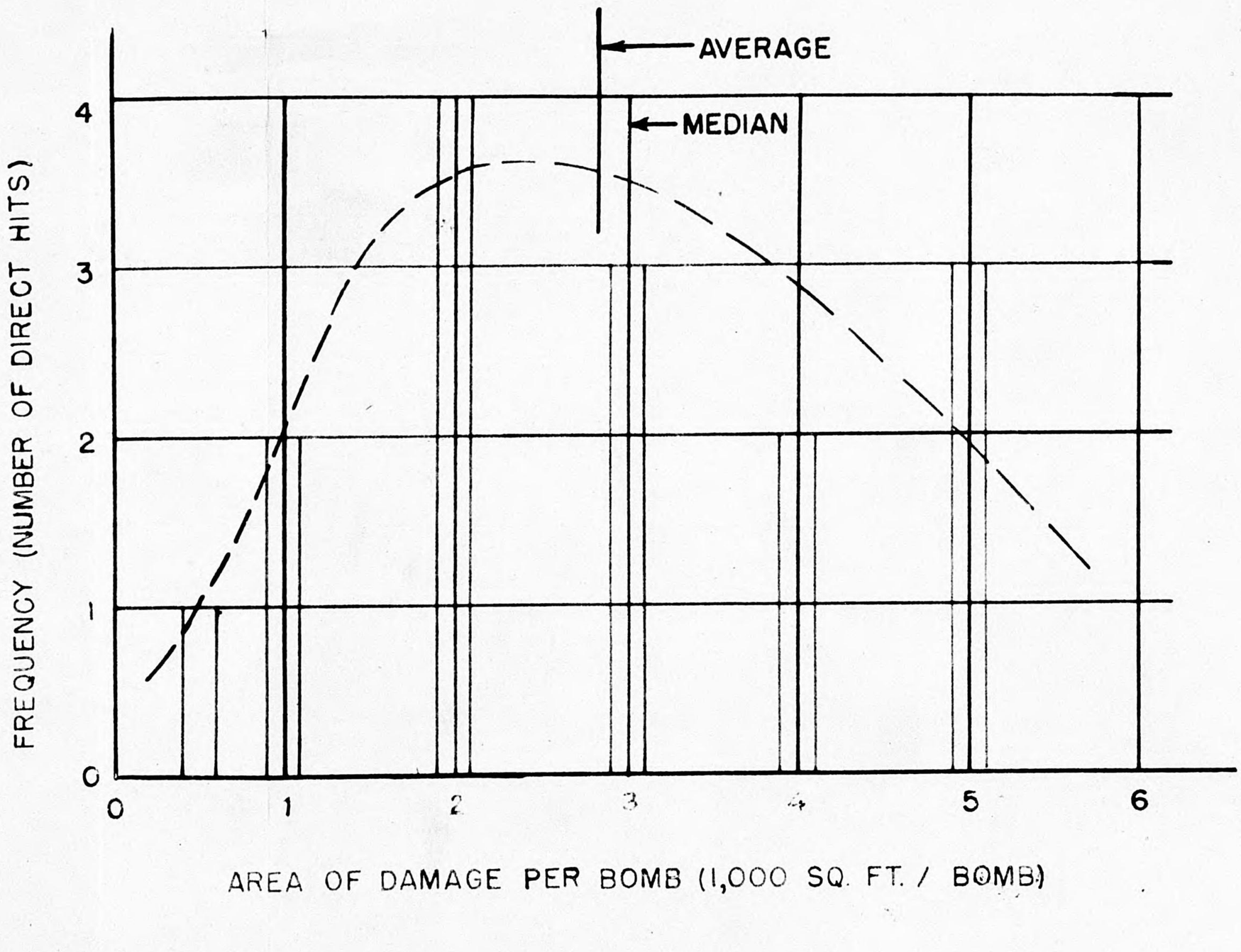
a. Figure 1 shows the distribution of structural damage per bomb for 15 non-cratering, 500-pound, general-purpose bombs which made direct hits on B2 (Table 1) steel buidlings at the Konan Plant of the Kawanishi Aircraft Co. As may be seen, the damage per bomb varied by a factor of 10. Four cratering bombs (same type of bomb, same target, same attack) caused no structural damage.

b. Figures 2 and 3 show the distributions of structural damage for direct hits with 1,000-pound, general-purpose bombs, 17 non-cratering and 12 cratering bombs, respectively. These hits were also on B2 steel buildings, but at the Narue Plant of the Kawanishi Aircraft Co. Again, the damage per bomb is seen to vary widely.

c. The curves of Figures 1 ~~to 3~~ and 2 were drawn by eye but are sufficiently similar in shape to suggest the existence of a general relationship for distribution of damage per bomb. Figure 3 indicates a tendency toward lower average damage for cratering bombs.

DISTRIBUTION OF STRUCTURAL DAMAGE PER BOMB

FOR 15 NON-CRATERING 500-LB. G.P. BOMBS



500-LB. G.P.; .01 SEC. DELAY NOSE, N.D. TAIL

KAWANISHI AIRCRAFT, KONAN PLANT

TYPE B2 BUILDINGS (JTG)

STRUCTURAL STEEL, LIGHT CRANES

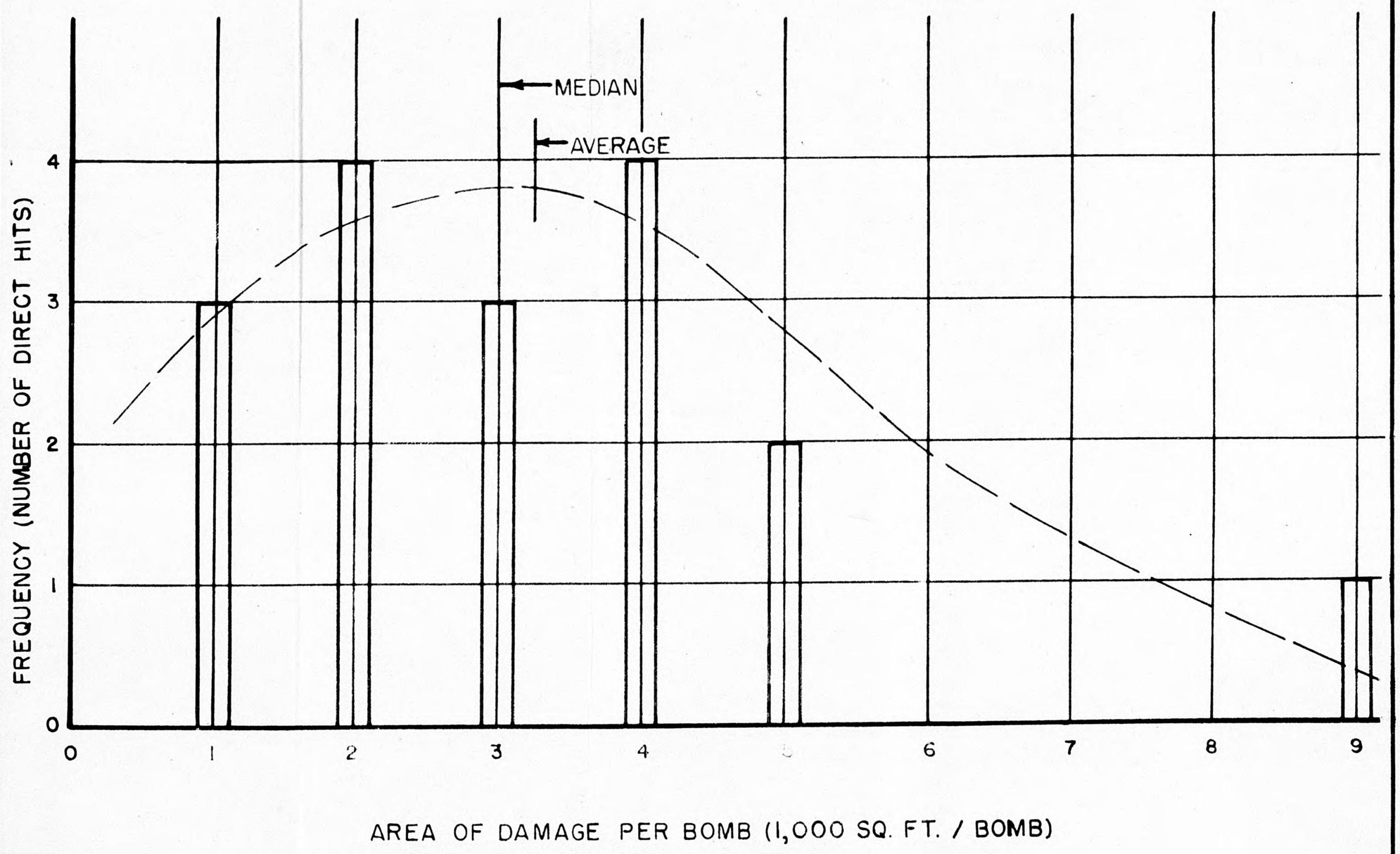
U.S. STRATEGIC BOMBING SURVEY

PHYSICAL DAMAGE

FIGURE-1

DISTRIBUTION OF STRUCTURAL DAMAGE PER BOMB

FOR 17 NON-CRATERING 1,000-LB. G.P. BOMBS



1,000-LB. G.P.; .01 SEC. NOSE DELAY, N.D. TAIL

KAWANISHI AIRCRAFT, NARUO PLANT

TYPE B2 BUILDINGS (JTG)

STRUCTURAL STEEL, LIGHT CRANES

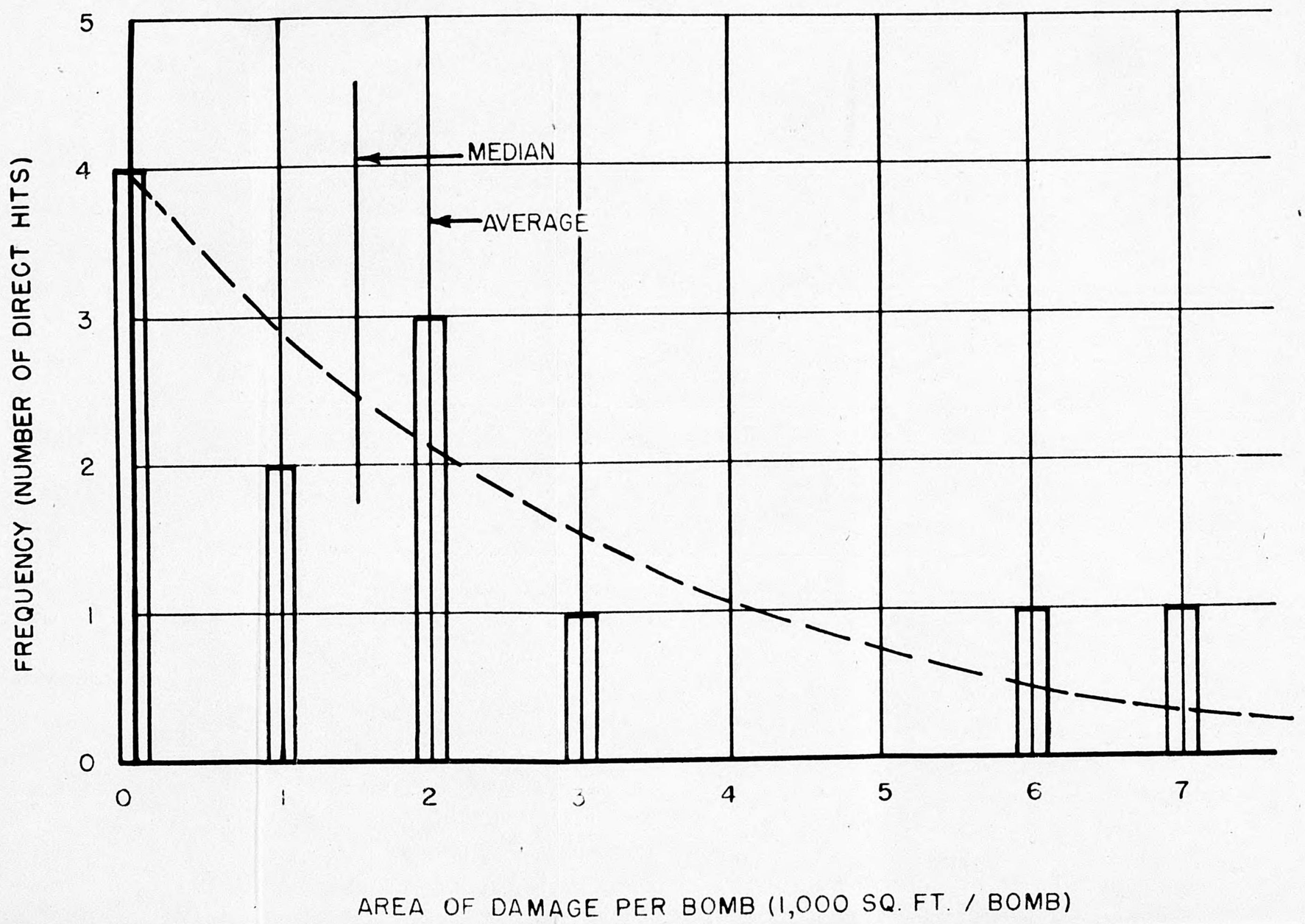
U.S. STRATEGIC BOMBING SURVEY

PHYSICAL DAMAGE

FIGURE 2

DISTRIBUTION OF STRUCTURAL DAMAGE PER BOMB

FOR 12 CRATERING 1,000-LB. G.P. BOMBS



1,000-LB. G.P.; .01 SEC. NOSE DELAY, N.D. TAIL

KAWANISHI AIRCRAFT, NARUO PLANT

TYPE B2 BUILDINGS (JTG)

STRUCTURAL STEEL, LIGHT CRANES

U.S. STRATEGIC BOMBING SURVEY

PHYSICAL DAMAGE

FIGURE 3

3 ~~2~~. The Mean Area of Effectiveness Concept. In casting about for a reliable yardstick for comparative bomb damage British analysts early hit upon the mean area of effectiveness (MAE) concept. MAE has been defined with many variations (a definition is given earlier in this chapter) but has survived this handicap and has proved a useful, comparative measure of bomb effectiveness. It is a mathematical concept which eliminates, in part, the difficulties introduced by near misses, built-upness, and overlap, although it can do nothing about the stout insistence of bomb-damage data to distribute themselves widely.

a. Methods of Calculating MAE. There are several methods of calculating MAE's. For an able and thorough presentation of the methods and the circumstances favorable to the use of each the reader is referred to R.E. Note 406, "Methods of Estimating the Mean Area of Effectiveness of H.E. Weapons against Buildings, Machine Tools and Similar Targets", Research and Experiments Department, British Ministry of Home Security. Briefly stated, they are:

(1) The Average-Circle Method: the area of a circle which encloses as many undamaged target units as it excludes damaged ones; applicable where effective radius is large compared to dimension of target unit, and the target area is highly built-up.

(2) The Annular-Ring Method: the sum of the products of areas of successive annuli about the bomb and the fractions of target units lying within them which are damaged; applicable wherever it is possible to make a

reasonable assignment of damage to bomb causing it; particularly useful with near misses.

(3) The Direct-Hit-Near-Miss Method: the sum of the direct-hit damage and the near-miss damage multiplied by their respective probabilities; applicable where effective radius is small compared to dimension of target unit, and where overlap is negligible; direct hits or near misses must be isolated.

(4) The Binomial Method: MAE is obtained from the formula,

$$M = \frac{N}{D}\left[1 - \left(1 - \frac{G}{A}\right)^{\frac{1}{N}}\right]$$

where M = MAE

N = Number of bombs

A = Area of target element

D = Density of bomb fall on target element

G = Total area of damage caused by N bombs.

If N is 10 or more and $\frac{G}{A}$ is $\frac{1}{2}$ or less, a close approximation may be obtained with the following exponential formula,

$$M = \frac{1}{D}\log_e\left[\frac{1}{1 - \frac{G}{A}}\right]$$

The binomial method, or its exponential approximation, assumes uniform distribution of bomb fall over the target area. It accounts for near-miss effect and for overlap. Reliable results will be obtained ~~is~~ if a fairly

uniform distribution of bomb fall has occurred and the target has not sustained a large number of hits bunched together. It is applicable where radius of effectiveness is small compared to dimension of target element.

F. PROCESSING OF DATA

1. Analysis of Data

a. Although it is considered that the data gathered by the Physical Damage Division in Japan are insufficient to furnish conclusive answers to the numerous questions regarding relative effectiveness of high-explosive bombs, it is believed nevertheless that they will serve as a significant addition to the meager store of information ~~already~~ previously in existence. An exhaustive analysis of the Division's Japanese data is not attempted; only the most significant comparisons and certain tentative conclusions are presented. An examination of Table ~~IV~~ 4 will reveal that although MAE's were computed for a number of building types and for several different bombs, they were often based upon a limited number of cases, so that data samples of adequate size for comparing effectiveness of the several bombs against a building type exist for only one or two.

b. An attempt has been made to determine whether or not these data, calculated from field measurement, do indicate a general relationship. Little is to be gained by saying, for instance, that the 4,000-pound, light-case bomb is $\frac{15.5}{12.5}$ or 1.24 times as effective as the 10,000-pound, light-case bombs against B2 steel buildings, unless there is assurance that 15.5 and 12.5 represent the statistical means for these

two bombs; the indications ~~is~~ are strong that they do not. The data have been tested by a criterion based upon the interaction between the structure and the dynamic loads imposed upon it by the blast wave. If the dynamic-reaction equation of a structure could be obtained, the efficiency of different bombs would follow from its solution. The theoretical determination of this equation is an almost prohibitively complicated task; hence, it is necessary to obtain the damage-reaction equation from the measured data. The method presented below was derived by the Operations Analysis Section, Headquarters, AAF.

(1) The Pressure-Impulse Vulnerability Curve. For each type of building there are many combinations of peak pressure and impulse of the blast wave which will be such as to cause the building to suffer structural damage. These combinations, if plotted, should define a smooth curve for each building type. The nature of this relationship is dependent upon the strength, mass and frequency of the structure, and its exact evaluation is difficult. However, certain deductions can be made about its general form.

(2) It is reasonable to expect that there is a certain minimum pressure which must be reached if damage is to be caused, whatever the value of the impulse. A loading less than the design load will not cause damage even though it acts so long that its impulse is essentially infinite. It is also reasonable to assume

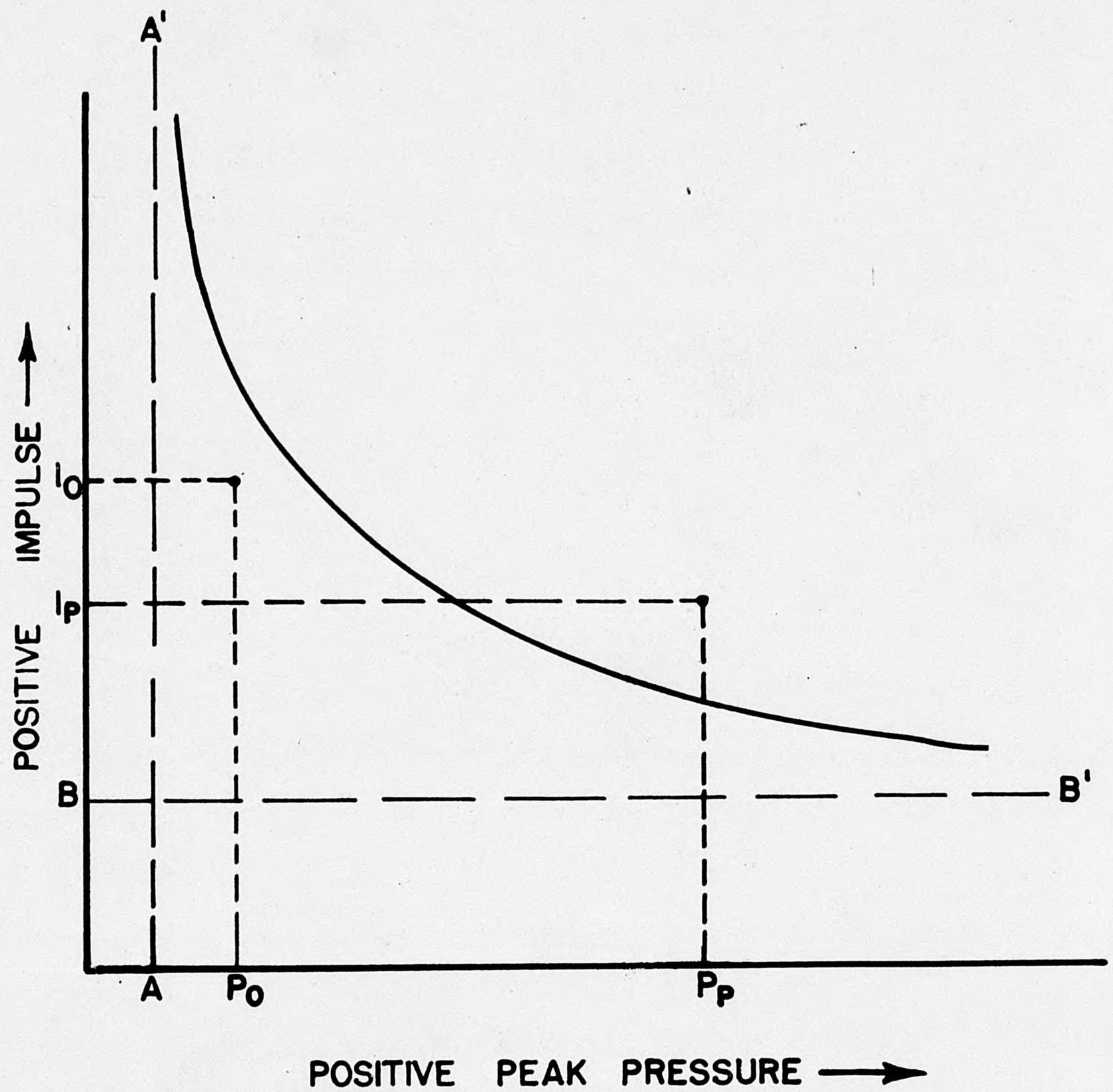
that there is a certain minimum impulse which must be reached if damage is to be caused, whatever the value of the pressure. That is, the structure must have enough momentum imparted to it by the blast impulse that its kinetic energy will carry it to failure.

(3) Between these two extremes there is no reason to expect any point of discontinuity, and, therefore, the relationship should follow a smooth transition. This suggests the type of curve shown in Figure 4. This curve may be called a pressure-impulse vulnerability curve. A-A' represents the minimum pressure which must be reached. B-B' represents the minimum impulse which must be reached. The pressure-impulse vulnerability curve will be asymptotic to A-A' and B-B', thus suggesting a curve of hyperbolic shape.

(4) If a structure were subjected to an impulse and pressure of (I_o, P_o) the structure would not be damaged. However, if it were subjected to an impulse of I_p and a pressure of P_p the structure would suffer damage.

2. <u>Test of Data</u>. Curves of the type illustrated in Figure 4 were constructed using the data of Table 4. Unfortunately, the B2-type steel building is the only type on which there are sufficient data to plot such a curve. Since, however, types A1.1 and A2.3 have been classed by JTG as being of the same vulnerability, a second curve was obtained by combining the data from these two building types.

PRESSURE—IMPULSE VULNERABILITY CURVE



U.S. STRATEGIC BOMBING SURVEY
PHYSICAL DAMAGE
FIGURE 4

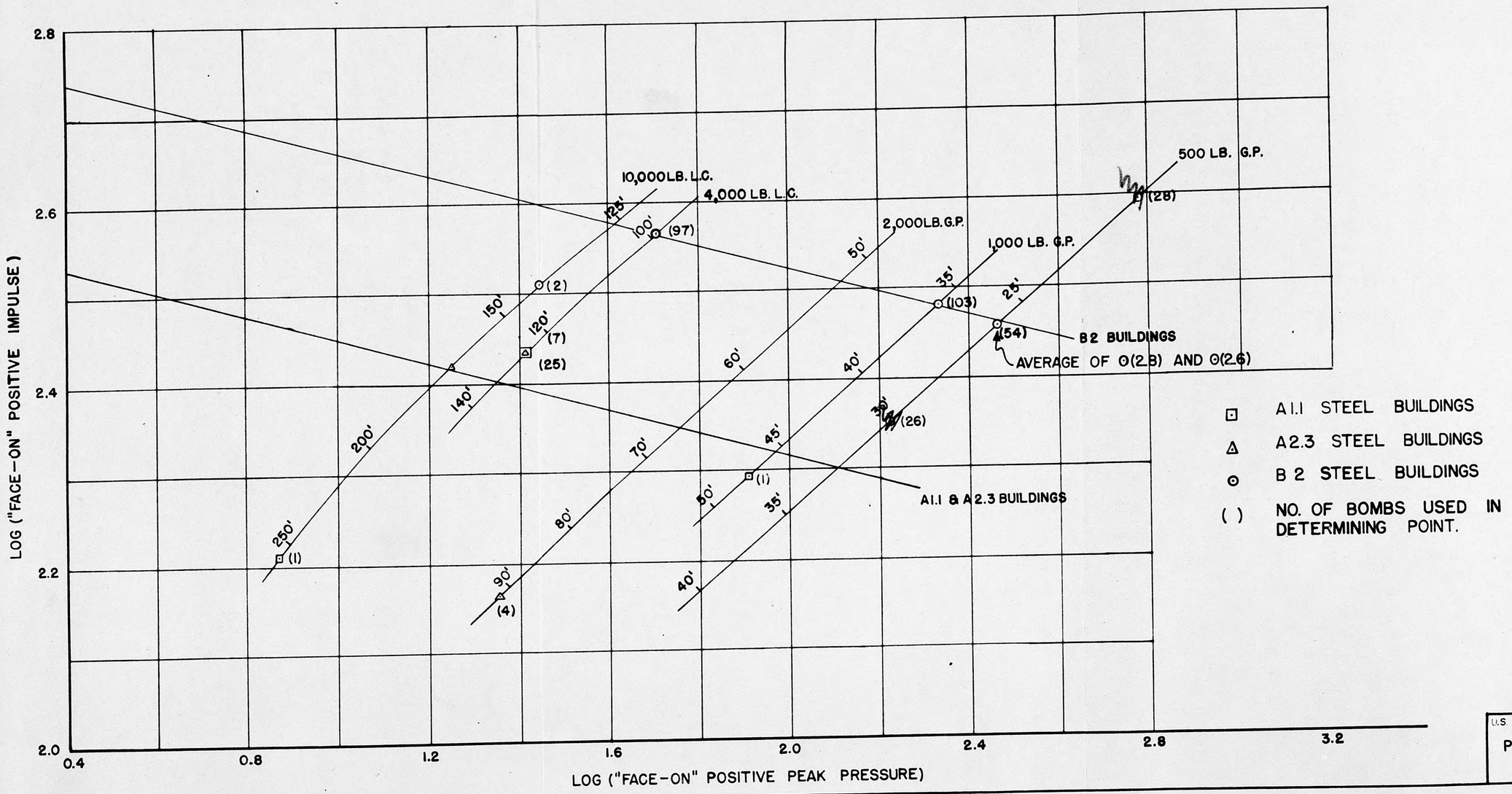
TABLE V

B2 Steel Buildings

Bomb Size	Fusing	No. of Bombs	Observed MAE 1,000 sq ft per ton of bomb	Probable Value of MAE (from curves) 1,000 sq ft per ton of bomb.
500-lb GP	ND-0.025	28	5.7	
"	ND-0.01	26	11.4	
"	Average	54	8.4	8.4
1,000-lb GP	ND-0.01	103	8.1	8.2
2,000-lb GP	ND-0.01			8.4
4,000-lb LC	ND-Inst.	97	15.5	15.5
10,000-lb LC	---Inst.	2	12.5	9.8

A1.1 and A2.3 Steel Buildings
Bldg Type

500-lb GP	ND-0.01				13.3
1,000-lb GP	ND-0.01	1	A1.1	14.1	13.0
2,000-lb GP	ND-0.01	4	A2.3	26.5	13.9
4,000-lb LC	ND-Inst.	25	A1.1	24.5	27.6
"	"	7	A2.3	24.7	
10,000-lb LC	---Inst.	1	A1.1	41.8	17.7
"	"	2	A2.3	17.6	



U.S. STRATEGIC BOMBING SURVEY

PHYSICAL DAMAGE

FIGURE 5

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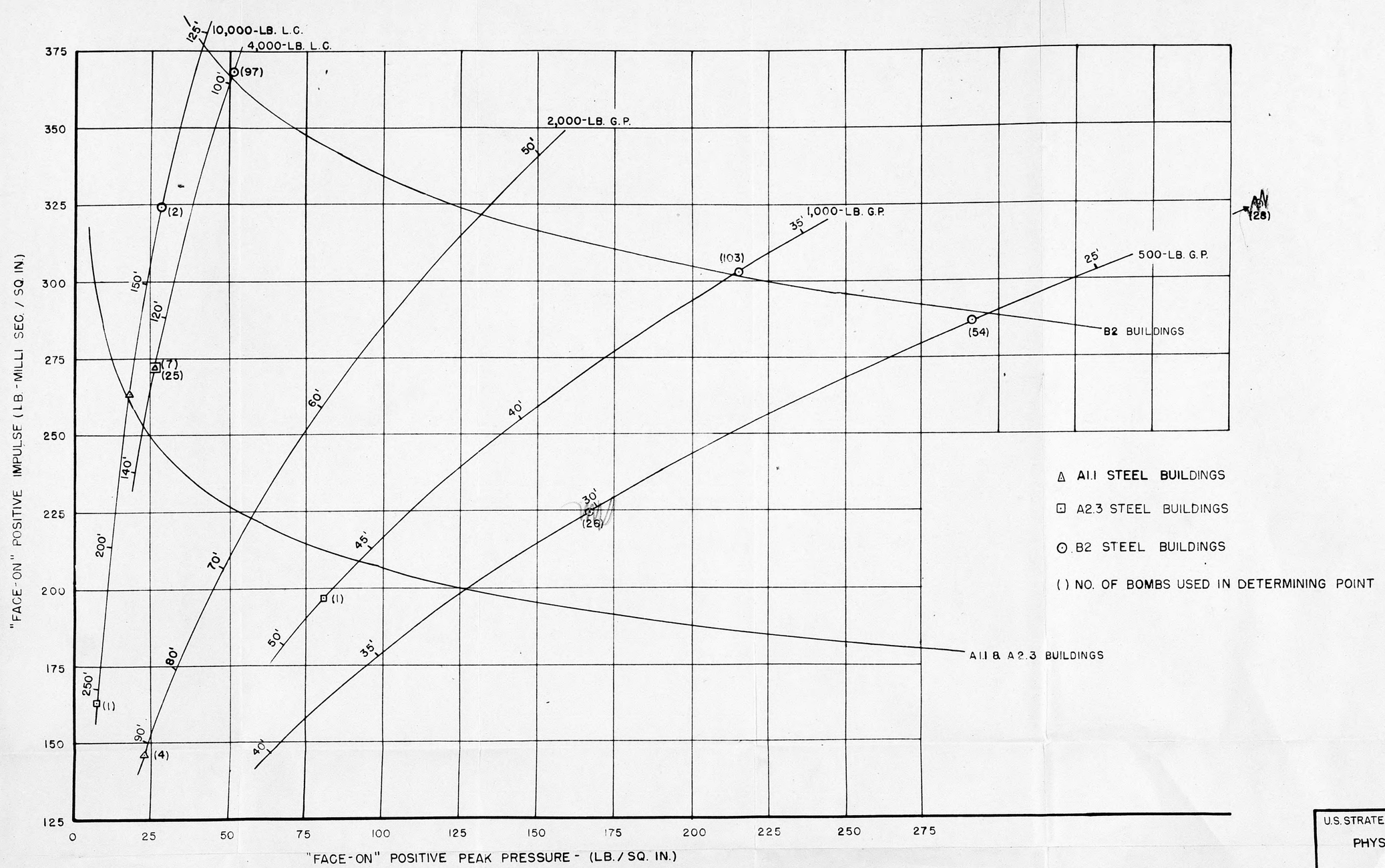


U.S. STRATEGIC BOMBING SURVEY

PHYSICAL DAMAGE

FIGURE-6

60

a. Assuming the pressure-impulse vulnerability curve to be hyperbolic a good approximation will be given by a straight line on a log-log plot. Figure 5 illustrates such a plot. On this plot are the pressure-impulse curves for the various bombs, and at the appropriate places representing the radii of the MAE's (assumed circular) are plotted the points of damage. Through the points for the B2 steel buildings a straight line was fitted by least squares, the points being weighted in proportion to the number of bombs. A line of the same slope was fitted by least squares to the points for A1.1 and A2.3 buildings.

b. Figure 6 represents the data on Figure 5 plotted to linear scales, giving curves of the type illustrated in Figure 4. It is not unusual for there to be a considerable spread of the data. Differences in the conditions of burst, construction, materials, or blast reflection would lead one to expect rather major variations. Despite these disadvantages which are inherent in the actual situation of bomb-versus-structure, this method provides, ~~however~~, a means for estimating the relative efficiency of different bombs without predetermining the result by assuming either a "pressure criterion" or an "impulse criterion".

3. <u>Results of Analysis</u>. In Table ~~V~~ 5 are presented the results of the analysis. MAE's from Table ~~IV~~ 4 are compared with those calculated from Figure 6. From the intersections of the pressure-impulse vulnerability curves and the curves of pressure and impulse for the bombs, radii of damage were scaled. MAE's were computed from these radii. The close correlation between calculated and observed MAE's suggests

that the data may be assumed to be reasonably reliable and that the pressure-impulse vulnerability curve may be used to predict MAE's for weapons for which observed data do not exist.

a. Order of Effectiveness. Table 5 indicates the probable order of effectiveness of five sizes of bombs against B2 steel buildings to be: (1) 4,000-pound light-case, (2) 10,000-pound light-case, (3) 500-pound general-purpose or 2,000-pound general-purpose, and (4) 1,000-pound general purpose. Similarly, the probable order of effectiveness against A1.1 and A2.3 steel buildings is: (1) 4,000-pound light-case, (2) 10,000-pound light-case, (3) 2,000-pound general-purpose, (4) 500-pound general-purpose, and (5) 1,000-pound general-purpose.

b. Malfunctioning of Bombs. Insufficient data were obtained to permit a numerical determination of frequency of malfunctioning of high-explosive bombs in Japan. The opinion, however, of members of several field teams was that malfunctioning was negligible with the possible exception of the 2,000-pound, general-purpose bomb in the early high-altitude attacks. Several unexploded bombs of this type were found at the Nakajima Musashino Aircraft Engine Plant in Tokyo; there was some evidence of flat-landers.

c. Percentage of Bombs on Target. Although no serious effort was made to determine the percentage of high-explosive bombs that hit within the target areas, the data listed in Table 6 and plotted in Figure 7 are interesting by-products of the field surveys.

(1) Table 6 shows that for nine Japanese industrial targets an average of 24 per cent of the bombs released over the target

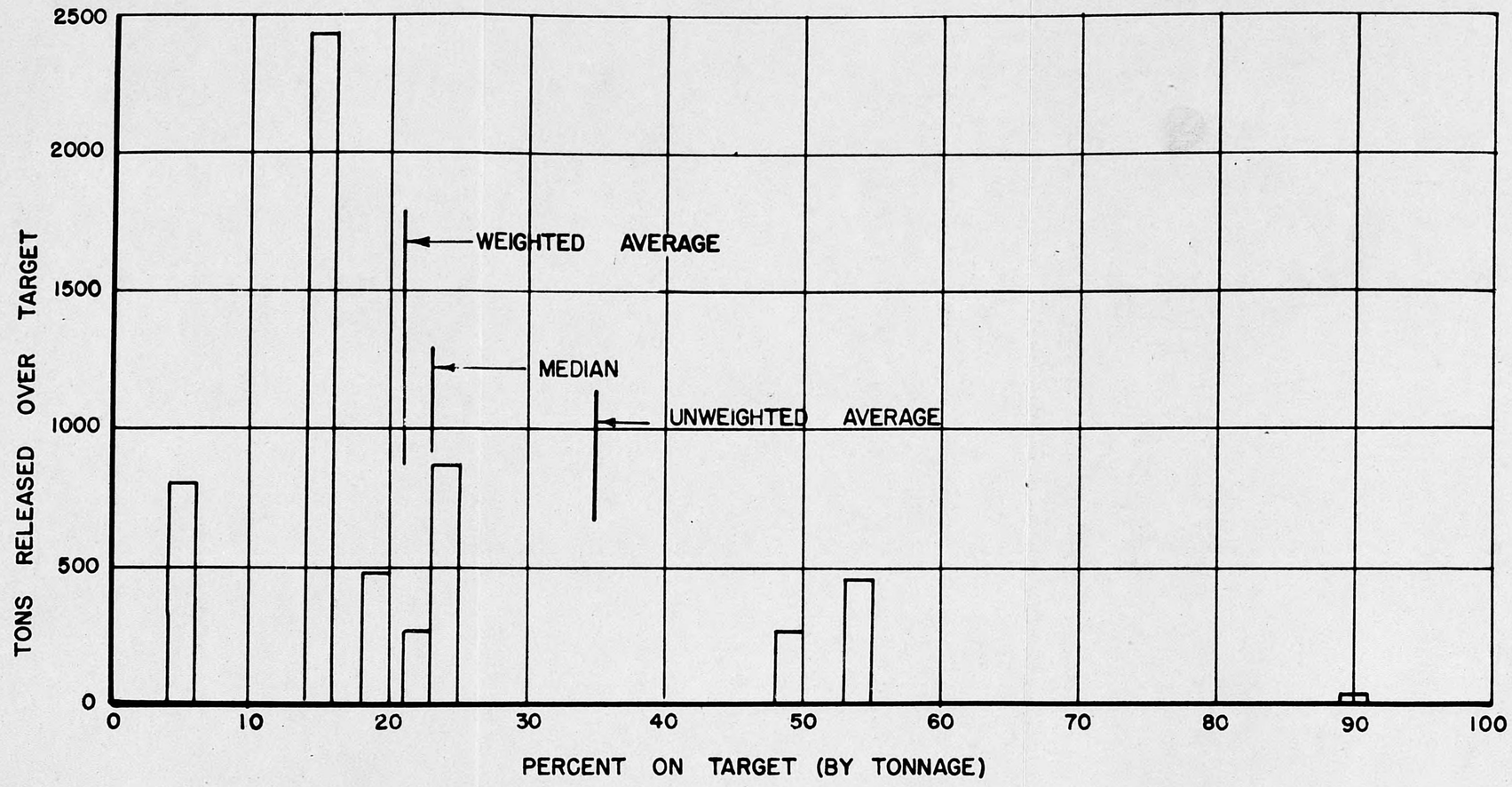
TABLE ~~VI~~ 6 PERCENTAGE OF BOMBS HITTING WITHIN TARGET AREA

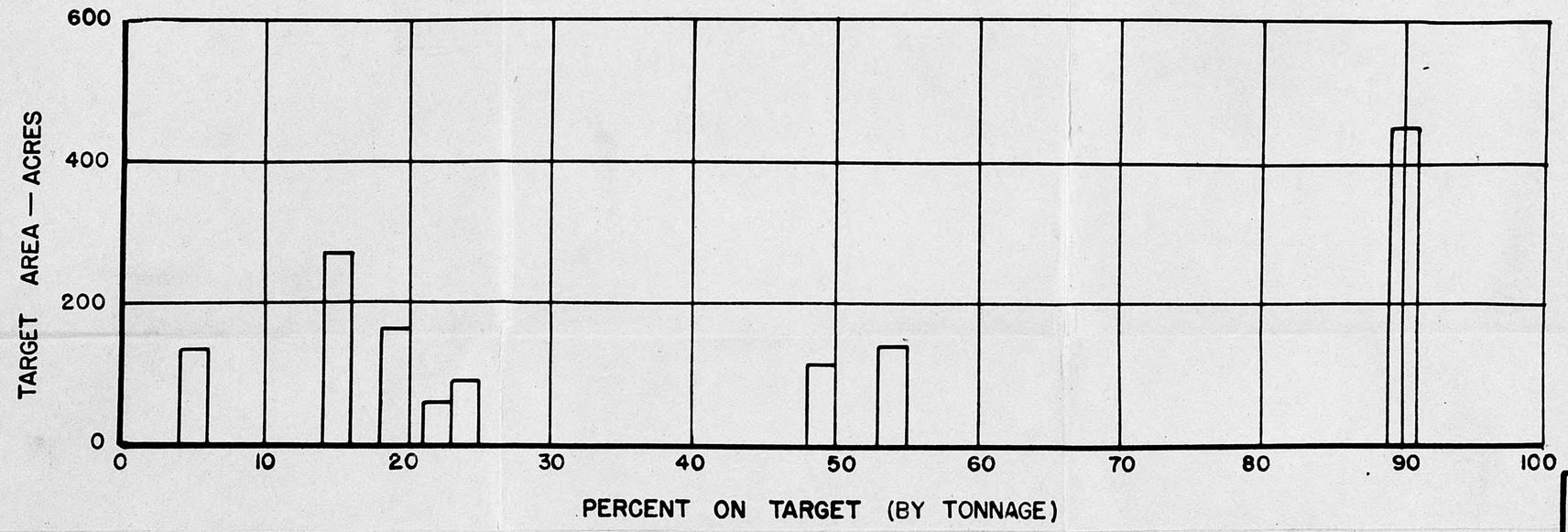
(For 9 Japanese Industrial Targets)

Name of Target	Tons of HE Released Over Target	Tons of HE Hit Within Target	Percentage on Target by Tonnage	Target Area in Acres	Number of HE Bombs Released Over Target	Number of HE Bombs Hit Within Target	Percentage on Target by Number of Bombs	Number of Bomb Hits on Buildings	Percentage of Hits on Buildings	Weight of Bomb in Pounds
1. Aichi-Atsuta A/C Engine	6	1.5			12	3		3		1000
Aichi - Funakata A/C Plant	23	3		18.0	23	3		3		2000
	242	54		42.3	121	27		15		4000
	271	58.5	22	60.3	156	33	21	21	13	
2. 2nd Naval Fuel Depot	1	1			1	1		1		2000
	40	36			20	18		3		4000
	41	37	90	457	21	19	90	4	20	
3. Kawasaki A/C Akashi	476	92	19	163	238	46	19	18	8	4000
4. Kawanishi A/C Takarazuka	450.5	244.5	54	141.3	901	489	54	111	12	1000
5. Osaka Arsenal	298.5	70			597	140				1000
	2125	285			2125	285				2000
	2423.5	355	15	273.2	2722	425	16	239	9	
6. Kawanishi A/C Naruo	263.5	128	49	117.4	527	256	49	130	25	1000
7. Sumitomo Metal Works, Niihama	870	208	24	91.5	435	104	24	85	20	4000
8. Aichi-Eitoku A/C Assembly	797	42	5	133	797	42	5	16	2	2000
Totals	5592.5	1165.0	21	159.6	5797	1414	24	624	11	

BOMBS ON TARGET AREA

(FOR A SAMPLE OF 8 JAPANESE TARGETS)





U.S. STRATEGIC BOMBING SURVEY

PHYSICAL DAMAGE
FIGURE 7

hit within the target areas; this figure is reduced to 21 per cent on a tonnage basis. Half of the bomb hits within the target areas were hits on buildings. It will be noted that there was considerable variation from target to target, ranging from 5 per cent to 90 per cent. Also of interest is the fact that the 5 per cent figure was for a target of 133 acres and the 90 per cent figure was for a 457-acre target, over three times as large.

(2) Figure 7 shows the relationship between percentage of bombs on target and both the total tonnage released over the target and the target size. Although these data will not support firm conclusions, a tendency toward decreased percentage on target with decrease in target size and with increase in total tonnage released is indicated.

Insert

CHAPTER III

FIRE AGAINST JAPAN

JAPANESE FINAL Add on Page 66

(Note: Throughout this report fire damage to urban areas is expressed in square miles of city area, including areas not built up, such as streets, parks, and canals. This method of evaluation differs from the procedure used in the Division's report on the European Theatre where fire damage was expressed in visible damage to buildings. These facts should be taken into consideration when comparing the two reports.

tons of incendiaries and 650 tons of high-explosive and fragmentation bombs, and causing nearly 100 per cent building damage in a total area of about 175 square miles--practically all in the very centers of the cities. Twenty minor missions, specific industrial and target-of-opportunity attacks, dropped an additional 12,000 tons of bombs on the same cities to damage another four square miles. (These figures are based on ground findings and photo interpretations which has been adjudged reasonably accurate.) Only one attacked city, Saga, was completely missed; Miyakonojo was hit but escaped serious damage because of the choice of bomb type and the low weight of the attack. The relative success of these major efforts is shown in Table 7, wherein are listed the cities, populations, and percentages of built-up areas burned. These figures indicate the extent but not the importance of the damage, for usually the heart of the city, that section with greatest density of families and houses and where trade was concentrated, was the area affected, while the remaining unburned portion was the less densely

Insert

CHAPTER III

FIRE AGAINST JAPAN

A. DEVELOPMENT OF INCENDIARY PROGRAM

1. Extent of Attacks. Warfare by fire from the sky reached its climax in the campaign conducted by the Twentieth AF against the Japanese homeland. The sweep and complexity of planning and execution in all phases reached the most impressive proportions in the history of aerial attack. Seventy-nine major missions were directed against 64 major cities, involving 13,365 aircraft sorties which dropped 93,000 tons of incendiaries and 650 tons of high-explosive and fragmentation bombs, and causing nearly 100 per cent building damage in a total area of about 175 square miles--practically all in the very centers of the cities. Twenty minor missions, specific industrial and target-of-opportunity attacks, dropped an additional 12,000 tons of bombs on the same cities to damage another four square miles. (These figures are based on ground findings and photo interpretations which has been adjudged reasonably accurate.) Only one attacked city, Saga, was completely missed; Miyakonojo was hit but escaped serious damage because of the choice of bomb type and the low weight of the attack. The relative success of these major efforts is shown in Table 7, wherein are listed the cities, populations, and percentages of built-up areas burned. These figures indicate the extent but not the importance of the damage, for usually the heart of the city, that section with greatest density of families and houses and where trade was concentrated, was the area affected, while the remaining unburned portion was the less densely

TABLE 17

A City	B DATE (1945)	C MISSION NUMBER	D PLANES REPORTED OVER TARGET	E NIGHT OR DAY	F ALTITUDE OF ATTACK	G NO A.P.	H INTERVALOMETER SETTINGS Path-finders	H INTERVALOMETER SETTINGS Main Force	I TIME OVER TARGET (min)	J HE & FRAGS (Tons)	K TONS BOMBS DROPPED 176 TONS	K %	L 174 TONS	L %	M 169 TONS	M %	N 147 TONS	N %	O 150 TONS	O %	P TOTAL TONS THIS ATTACK	Q SQ. MILE DAMAGE THIS ATTACK	R DAMAGE-WEIGHT INDEX	S TOTAL TONS ON CITY ALL ATTACKS	T * TOTAL DEATHS ALL ATTACKS	U POPULATION	V SQ MI BUILT UP	W PERCENTAGE OF CITY DAMAGED THIS ATTACK
Akashi	6 July	252	123	N	7,000	1	50	50	72						975	100					975	1.06	1.09	975	1421	90,000	1.2	60
Aomori	28 July	299	61	N	14,000	1	50	50	71				547	100							547	1.06	1.94	547	1018	100,000	1.65	64
Chiba	6 July	251	124	N	10,000	1	75	50	86	31					486	59	371				888	.86	.97	888	856	92,000	1.98	43
Chosi	19 July	279	91	N	10,200	1	50	35	81	31					598	95/100					629	.48	.76	693	394	61,200	1.12	43
Fukui	19 July	277	124	N	12,400	1	50	75/50	81						756	80	195				951	1.61	1.81	961	1504	98,000	1.90	85.0
Fukuoka	16 Jun	211	221	N	9,000	1	100	100/50	102						530		1003	66			1533	1.37	.89	1533	953	323,200	6.56	21.5
Fukuyama	18 August	321	91	N	13,100	1	75	35	70								139		417	75	556	.88	1.58	556	275	56,653	1.20	73
Gifu	9 July	260	129	N	14,700	1	100	100/50	106						477	53	421				898	1.93	2.15	898	818	172,340	2.60	74
Hachioji	1 August	306	169	N	14,800	1	50	50	104								69		1525	96	1594	1.15	.72	1594	290	62,280	1.40	82
Hamamatsu	17 June	208	130	N	7,900	1	75	75/50	66						491	52	413		32		936	2.44	2.61	1056	2947	166,350	4.24	57.5
Himeji	3 July	249	106	N	10,100	1	100	100/50	82						547	71	221				768	1.48	1.93	768	514	104,250	1.92	71
Hiratsuka	16 July	274	133	N	10,900	1	100	50	100								240		923	80	1163	1.04	.89	1103	228	43,150	2.35	44
Hitachi	3 July	279	127	N	12,800	1	50	75/50	93						250		394	41	320		964	1.08	1.12	971	1019	82,700	1.38	78
Ichinomiya	16 July	264	124	N	6,000	1	75	75	111								772	100			772	.01				70,800	1.28	
Ichinomiya	28 July	299	123	N	13,500	1	50	50	112						485	56	378		5		863	.96	1.10	1640	648	70,800	1.28	75
Imabari	5 August	316	64	N	12,200	1	35	35	42	20					490	100/98					510	.69	1.35	629	242	60,000	.97	76
Isesaki	14 August	330	87	N	15,500	1	25	25	127						343	56	271				614	.166	.27	614	9	40,000	1.00	16
Kagoshima	17 June	206	117	N	7,000	1	75	75/50	103						447	55	355		8		810	2.15	2.66	969		190,250	4.87	44
Kawasaki	15 April	88	194	N	5-7,900	2	100	50	142	37.6					764	70	308				1110	3.7	3.33	1515	1520	300,770	11.3	33
Kobe	16 March	43	296	N	6-7,000	4	50	50	128	19.4	376				653				1283	56	2331	2.9	1.24		6887)	300,770	11.3	18
Kobe	4 June	188	307	D	13-15,000	4			85	71.0					942		1132	37	452		3097	4.35	1.45	5667	)	967,234	15.7	37
Kochi	3 July	218	125	N	10,300	1	100	100/50	60		313				748	71					1061	.92	.87	1061	447	106,650	1.9	48
Kofu	6 July	254	131	N	11,200	1	75	50	108						731	75	232		8		971	1.30	1.34	977.9	832	102,400	2.0	65
Kumagaya	14 August	329	82	N	14-14,000	1	25	25	76	8.0					274	47	218		89		581	.27	.46	593	242	49,000	.6	45
Kumamoto	1 July	241	155	N	10-11,000	2	100	50	91				48		702	62	375				1125	1.00	.89	1491	583	211,000	4.8	21
Kure	1 July	240	152	N	10,300	1	100	50	123						612	52	470				1082	1.30	1.20	1082	1967	277,000	3.26	40
Kurume	16 July	273	94	N	10,200	1	50	35	75						492	71	201				693	.63	.91	693	421	41,850	.82	77
Maebashi	5 August	313	92	N	15,200	1	35	35	100	15.2					691	100/98					706	1.00	1.42	723	471	87,000	2.34	42
Matsuyama	26 July	293	128	N	11,000	1	50	50	130						487	54	394		15		896	1.22	1.36	896	380	117,530	1.67	73
Mito	1 August	309	161	N	12,000	1			94						642	56	510				1152	1.70	1.47	1152	205	66,300	2.60	65
Miyakonjo	6 August	-	27	D	1,000	-			-				165 gallon belly tanks				20				229	0				-		0
Moji	28 June	236	91	N	9,000	1	100	100/50	92						253		373	60			626	.30	.48	626	161	139,000	1.12	27
Nagaoka	1 August	308	125	N	12,100	1			75						849	92	76				925	1.33	1.44	925	831	67,000	2.03	65
Nagoya	11 March	41	280	N	6,000	3	100	100	178						1689	94	104				1793	2.05	1.14		3152)	1,328,000	40.0	5
Nagoya	18 March	44	290	N	4,5-7,000	3	100	50	164	19	495				274		959	52	116		1863	2.95	1.58		)	1,328,000	40.0	7
Nagoya	18 April	174	472	D	16,000	4	25	25	80						2515	100					2515	3.15	1.25		)	1,328,000	40.0	8
Nagoya	16 April	176	457	N	6-10,000	4	100	50	173						75		127		3407	96	3609	3.82	1.06	10603		1,328,000		10
Nishinomiya	5 August	314	255	N	12,6-13,000	2	35	35	29	33.5					1795	92	94		33		1955	3.50	1.79	2004	749	111,800	12.03	37
Nobeoka	28 June	237	117	N	7,000	1	100	100/50	91						483	58	346				829	.52	.63	853	284	79,426	1.43	36
Numazu	16 July	271	119	N	10,600	1	75	50	99						8		197		831	80	1036	1.25	1.21	1051	267	53,165	1.40	90
Ogaki	28 July	301	92	N	14,000	1	50	50	118						360	55	289		10		659	.48	.73	659	61	56,100	1.20	40
Oita	16 July	272	127	N	10,000	1	75	75	80								790	100			790	.42	.53	824	177	61,000	1.6	26
Okayama	28 June	234	138	N	11,000	1	100	100/50	24				547	56			435				982	2.13	2.17	982	1745	163,560	3.38	63

TABLE 17

A City	B DATE (1945)	C MISSION NUMBER	D PLANES REPORTED OVER TARGET	E NIGHT OR DAY	F ALTITUDE OF ATTACK	G NO A.P.	H INTERVALOMETER SETTINGS Path-finders	H INTERVALOMETER SETTINGS Main Force	I TIME OVER TARGET (min)	J TONS BOMBS DROPPED HE & FRAGS (Tons)	K M76 TONS	K M76 %	L M74 TONS	L M74 %	M M69 TONS	M M69 %	N M47 TONS	N M47 %	O M50 TONS	O M50 %	P TOTAL TONS THIS ATTACK	Q SQ. MILE DAMAGE THIS ATTACK	R DAMAGE-WEIGHT INDEX	S TOTAL TONS ON CITY ALL ATTACKS	T TOTAL DEATHS ALL ATTACKS	U POPULATION	V SQ MI BUILT UP *	W PERCENTAGE OF CITY DAMAGED THIS ATTACK
Akashi	6 July	252	123	N	7,000	1	50	50	72						975	100					975	1.06	1.09	975	1421	90,000	1.2	60
Aomori	28 July	299	61	N	14,000	1	50	50	71				547	100							547	1.06	1.94	547	1018	100,000	1.65	64
Chiba	6 July	251	124	N	10,000	1	75	50	86	31					486	59	371				888	.86	.97	888	856	92,000	1.98	43
Chosi	19 July	279	91	N	10,200	1	50	35	81	31					598	95/100					629	.48	.76	693	394	61,200	1.12	43
Fukui	19 July	277	124	N	12,400	1	50	75/50	81						756	80	195				951	1.61	1.81	961	1504	98,000	1.90	85.0
Fukuoka	16 Jun	211	221	N	9,000	1	100	100/50	102						530		1003	66			1533	1.37	.89	1533	953	323,200	6.56	21.5
Fukuyama	18 August	321	91	N	13,100	1	75	35	70								139		417	75	556	.88	1.58	556	275	56,653	1.20	73
Gifu	9 July	260	129	N	14,700	1	100	100/50	106						477	53	421				898	1.93	2.15	898	818	172,340	2.60	74
Hachioji	1 August	306	169	N	14,800	1	50	50	104								69		1525	96	1594	1.15	.72	1594	290	62,280	1.40	82
Hamamatsu	17 June	208	130	N	7,900	1	75	75/50	66						491	52	413		32		936	2.44	2.61	1056	2947	166,350	4.24	57.5
Himeji	3 July	249	106	N	10,100	1	100	100/50	82						547	71	221				768	1.48	1.93	768	514	104,250	1.92	71
Hiratsuka	16 July	274	133	N	10,900	1	100	50	100								240		923	80	1163	1.04	.89	1103	228	43,150	2.35	44
Hitachi	3 July	279	127	N	12,800	1	50	75/50	93						250		394	41	320		964	1.08	1.12	971	1019	82,700	1.38	78
Ichinomiya	16 July	264	124	N	6,000	1	75	75	111								772	100			772	.01				70,800	1.28	
Ichinomiya	28 July	299	123	N	13,500	1	50	50	112						485	56	378		5		863	.96	1.10	1640	648	70,800	1.28	75
Imabari	5 August	316	64	N	12,200	1	35	35	42	20					490	100/98					510	.69	1.35	629	242	60,000	.97	76
Isesaki	14 August	330	87	N	15,500	1	25	25	127						343	56	271				614	.166	.27	614	9	40,000	1.00	16
Kagoshima	17 June	206	117	N	7,000	1	75	75/50	103						447	55	355		8		810	2.15	2.66	969		190,250	4.87	44
Kawasaki	15 April	88	194	N	5-7,900	2	100	50	142	37.6					764	70	308				1110	3.7	3.33	1515	1520	300,770	11.3	33
Kobe	16 March	43	296	N	6-7,000	4	50	50	128	19.4	376				653				1283	56	2331	2.9	1.24		6887)	300,770	11.3	18
Kobe	4 June	188	307	D	13-15,000	4			85	71.0					942		1132	37	452		3097	4.35	1.45	5667	)	967,234	15.7	37
Koshi	3 July	248	125	N	10,300	1	100	100/50	60		313				748	71					1061	.92	.87	1061	447	106,650	1.9	48
Kofu	6 July	254	131	N	11,200	1	75	50	108						731	75	232		8		971	1.30	1.34	977.9	832	102,400	2.0	65
Kumagaya	14 August	329	82	N	14-14,000	1	25	25	76	8.0					274	47	218		89		581	.27	.46	593	242	49,000	.6	45
Kumamoto	1 July	241	155	N	10-11,000	2	100	50	91				48		702	62	375				1125	1.00	.89	1491	583	211,000	4.8	21
Kure	1 July	240	152	N	10,300	1	100	50	123						612	52	470				1082	1.30	1.20	1082	1967	277,000	3.26	40
Kuwana	16 July	273	94	N	10,200	1	50	35	75						492	71	201				693	.63	.91	693	421	41,850	.82	77
Maebashi	5 August	313	92	N	15,200	1	35	35	100	15.2					691	100/98					706	1.00	1.42	723	471	87,000	2.34	42
Matsuyama	26 July	293	128	N	11,000	1	50	50	130						487	54	394		15		896	1.22	1.36	896	380	117,530	1.67	73
Mito	1 August	309	161	N	12,000	1			94						642	56	510				1152	1.70	1.47	1152	205	66,300	2.60	65
Miyakonjo	6 August	-	27	D	1,000	-			-				165 gallon belly tanks				20				229	0				-		0
Moji	28 June	236	91	N	9,000	1	100	100/50	92						253		373	60			626	.30	.48	626	161	139,000	1.12	27
Nagaoka	1 August	308	125	N	12,100	1			75						849	92	76				925	1.33	1.44	925	831	67,000	2.03	65
Nagoya	11 March	41	280	N	6,000	3	100	100	178						1689	94	104				1793	2.05	1.14		3152)	1,328,000	40.0	5
Nagoya	18 March	44	290	N	4,5-7,000	3	100	50	164	19	495				274		959	52	116		1863	2.95	1.58		)	1,328,000	40.0	7
Nagoya	18 April	174	472	D	16,000	4	25	25	80						2515	100					2515	3.15	1.25		)	1,328,000	40.0	8
Nagoya	16 April	176	457	N	6-10,000	4	100	50	173						75		127		3407	96	3609	3.82	1.06	10603		1,328,000		10
Nishinomiya	5 August	314	255	N	12,6-13,000	2	35	35	29	33.5					1795	92	94		33		1955	3.50	1.79	2004	749	111,800	12.03	37
Nobeoka	28 June	237	117	N	7,000	1	100	100/50	91						483	58	346				829	.52	.63	853	284	79,426	1.43	36
Numazu	16 July	271	119	N	10,600	1	75	50	99						8		197		831	80	1036	1.25	1.21	1051	267	53,165	1.40	90
Ogaki	28 July	301	92	N	14,000	1	50	50	118						360	55	289		10		659	.48	.73	659	61	56,100	1.20	40
Oita	16 July	272	127	N	10,000	1	75	75	80								790	100			790	.42	.53	824	177	61,000	1.6	26
Okayama	28 June	234	138	N	11,000	1	100	100/50	24				547	56			435				982	2.13	2.17	982	1745	163,560	3.38	63

TABLE 19 (continued)

A	B	C	D	E	F	G	H		I	J	K	L		M		N		O		P	Q	R	S	T	U	V	W
							INTERVALOMETER SETTINGS																				
CITY	DATE (1945)	MISSION NUMBER	PLANES REPORTED OVER TARGET	NIGHT OR DAY	ALTITUDE OF ATTACK	NO.	Path-Finders	Main Force	TIME OVER TARGET (min)	HE & FRAGS (Tons)	M76 TONS	%	M74 TONS	%	M69 TONS	%	M47 TONS	%	M50 TONS	%	TOTAL TONS THIS ATTACK	SQ. MILE DAMAGE THIS ATTACK	DAMAGE-WEIGHT INDEX †	TOTAL TONS ON CITY ALL ATTACKS	TOTAL DEATHS ALL ATTACKS *	POPULATION	SQ. MI BUILT UP *	PERCENTAGE OF CITY DAMAGED THIS ATTACK
Okasaki	19 July	280	126	N	12,700	1	75	75/50	78						495	58	327		29		851	.65	.76	851	151	84,070	.95	68
Omuta	17 June	207	116	N	6,600	1	75	75/50	129						369		401	52			770	.217	.28	770	780)	177,000	5.37	4
Omuta	26 July	295	124	N	13,100	1	50	50	79								380		585	61	965	2.05	2.12	965	)	177,000	5.37	38
Osaka	13 March	42	264	N	5-6,000	3	100	50	208						1678	97	55				1733	8.1	4.67	1733	9915)	3,252,340	60.0	13
Osaka	31 May	187	458	D	18-20,000	5	75	75/35	92	81					698		1328	48	680		2707	3.15	1.13				"	5
Osaka	6 June	189	409	D	18,000	5	75	75/35	79	47			196		556		1046	58			1855	2.21	1.20		)		"	4
Osaka & Amagasaki	15 June	203	390	D	18,000	4	75	75/35	131						69		507		2581	85	3157	2.49	.79	9514	)	3,433,340	67.0	4
Saga	5 August	312	63	N	12,400	1	35	35	95	72					439	100/86					511	.02		511	25	50,400	1.2	
Sakai	9 July	258	116	N	10,000	1	100	100/50	93						412	53	367				779	1.02	1.31	779	1411	182,150	2.32	44
Sasebo	28 June	235	140	N	10,100	1	100	100/50	76		262		221		34				543	51	1060	.97	.91	1070	1000	206,000	2.34	42
Sendai	9 July	257	125	N	10,000	1	100	100/50	122						13		376		539	58	928	1.22	1.32	1018	992	233,630	4.53	27
Shimizu	6 July	253	133	N	7,100	1	50	50/35	97								435		595	58	1030	.74	.71	1042	351	68,600	1.41	52.5
Shimonosaki	1 July	243	126	N	7,000	1	100	50	35						491	59	342				833	.51	.61	837	241	198,000	1.42	36
Shizuoka	19 June	212	123	N	8,000	1	75	75/50	123						499	57	370				869	2.28	2.62	1022	1952	212,200	3.46	56
Takamatsu	3 July	247	116	N	9,900	1	100	50	106	24.3					463	56	346				833	1.40	1.68	833	1273	111,200	1.80	72
Tokushima	3 July	250	129	N	10,200	1	100	100/50	110								404		647	61	1051	1.70	1.62	1127	1070	119,600	2.30	74
Tokuyama	26 July	294	98	N	11,000	1	50	50	73						642	82	76				718	.68	.95	718	942	38,400	1.27	53
Tokyo	25 February	38	172	D	23-25,000	1	25	25	114	42.2					412	100/87					454	1.00	2.20		)	6,778,800	163.0	1
Tokyo	9 March	40	279	N	5-7,000	4	100	50	173						1539	92	128				1667	15.8	9.48		86000)	"	"	10
Tokyo	13 April	67	328	N	6-9,000	3	100	50	219	81.9					1820	85	222				2124	11.4	5.37		)	"	"	7
Tokyo	15 April	69	109	N	8,000	1	100	50	142	14.5					434	56	320				764	6.0	7.80		all)	"	"	8
Tokyo	23 May	181	520	N	8-10,000	6	100	50	119						2820	77	777		49		3646	5.3	1.45		other)	"	"	3
Tokyo	25 May	183	464	N	7,9-8,700	6	25	100/50	155	4.0	348				1320	41	694		945		3251	15.8	5.17	14054	7000	"	"	11
Toyama	1 August	307	175	N	12,100	1			111						67		274		1131	77	1472	1.87	1.27	1472	2149	127,860	1.88	99
Toyohasi	19 June	210	136	N	8,800	1	100	100/50	139						518	55	420		8		946	1.7	1.80	1026	576	142,700	3.3	52
Tsu	28 July	297	76	N	11,000	1	50	50	69				730	100							730	.84	1.15	1507	1498	68,625	1.47	81
Tsuruga	12 July	265	93	N	12,200	1	50	35	187						477	70	206				683	.77	1.13	683	161	31,350	1.13	68
Ube	1 July	242	101	N	10,000	2	100	50	85						532	74	185				712	.49	.68	722	336	100,600	1.80	27
Ujiyamada	28 July	300	93	N	12,000	1	35	35	69						735	100					735	.36	.49	735	102	52,555	.93	39
Utsonomiya	12 July	263	115	N	13,300	1	75	75/35	131						441	55	362				803	.94	1.17	803	570	87,868	2.73	34
Uwajima	12 July	266	124	N	10,400	1	75	75/50	133						479	55	393				872	.14	.16	872	248)	52,100	1.0	14
Uwajima	28 July	302	29	N	10,400	1	50	50	69						115	56	90				205	.35	1.71	1089	)	"	"	35
Wakayama	9 July	259	108	N	10,200	1	100	100/50	120								442	55	359		801	2.10	2.62	854	1625	195,200	4.0	52.5
Yawata	7 August	319	221	N	19-22,000	3	75	75/35	35						133				1169	89	1302	1.22	.94	1302	1996	261,300	5.76	21
Yokkaichi	17 June	209	89	N	7,000	1	75	75/50	79						195		352	62	20		567	1.23	2.17	591	834	102,770	3.51	35
Yokohama	28 May	186	454	D	17,5-18,000	5			75						1782	69	767		21		2570	8.9	3.46	2590	4832	968,090	20.2	44

* ~~See first page~~ Populated area including parks and small rivers within the city

* ~~See first page~~ All deaths from all attacks are given in cities of multiple attacks

† ~~See first page~~ Damage - Weight Index = Sq. mi. of damage per 1000 tons of bombs