and the necessity of finding a valid yardstick for comparison, forced the selection of only the major attacks for inclusion in this report.

a. The Major Attacks. Five of the 12 Tokyo attacks which included 85 per cent of the total tonnage dropped were chosen for summarization and comparison. Four of the five Nagoya attacks which included 96 per cent of the total tonnage dropped were similarly chosen. These nine attacks caused over 98 per cent of the damage in the two cities. They are summarized in Table 27 from which some general observations can be made as follows:

(1) The tactics and weapons employed were generally similar.

(2) The attacks against the two cities were made during approximately the same period.

(3) No firm conclusions can be drawn from the efficiencies of these attacks as related to the frequency with which they occurred, how closely they followed each other, the number of planes over the target, the total tonnage dropped, the principal bomb used, the cluster or intervalometer set, or the time over the target.

(4) Up-wind runs seemed to be generally less effective then down-wind and cross-wind runs. Two of the four runs against Nagoya were up-wind while only one of the six against Tokyo was up-wind.

TABLE 27 - PRINCIPAL RAIDS ON TOKYO AND NAGOYA

	Number of Mission	Date	Planes Over Target	Number of Aiming Points	Altitude (1,000 ft)	Intervalometer Setting P-Pathfinder Planes M-Main Attacking Force	Total Tons Dropped	Total Tons HE	Total Tons M69	Total Tons M47	Total Tons M50	Total Tons M76	Cluster to open at	Sq Mi Destroyed	Sq Mi Destroyed per 100 tons	Preponderant Bomb Type Percentage	Minutes Over Target
T	40	9/3	279	4	4.9-9.2	100'P 50'M	1665.0	0	1538.1	126.9	0	0	2,000-2,500'	15.8	.948	92% M69's	173
O	67	13/4	327	3	6.8-11.0	100'P 50'M	2119.6	81.9	222.3	1815.4	0	0	2,500'	11.4	.538	86% M47's	
K	69	15/4	109	1	8.0 10.1	100'P 50'M	768.9	14.5	434.4	320.0	0	0	2,500'	6.0	.780	56% M69's	
Y	181	23/5	520	6	7.8-15.1	100'P 50'M	3645.7	0	2819.6	777.3	48.8	0	5,000'	3.2	.088	77% M69's	
O	183	25/5	464	6	7.9-22.0	100'P 50'M	3262.0	4.0	1323.1	633.7	953.7	347.5	5,000'	18.6	.570	41% M69's	
TOTAL			1871				11914.9	142.7	6748.9	3673.3	1002.5	347.5		56.0	av. .470	57% of M69's	
N	41	11/3	280	3	6.8-7.3	100'P 100'M	1789.8	0	1677.4	112.4	0	0	2,000-2,500'	1.2	.067	94% M69's	178
A	44	18/3	290	3	4.0-7.5	100'P 50'M	1857.5	19.2	271.9	958.4	114.5	493.5	2,000-3,000'	3.0	.162	52% M47's	164
G	174	13/5	472	4	12.0 20.5	25'	2515.1	0	2515.1	0	0	0	5,000'	3.2	.127	100% M69's	80
O	176	16/5	457	4	6.6-18.3	50'	3609.0	0	75.6	126.7	3406.7	0	3,000'	3.8	.105	94% M50's	173
Y																	
A																	
TOTAL			1499				9771.4	19.2	4540.0	1197.5	3521.2	493.5		11.2	.115	46% M69's	495

(5) Effectiveness seemed to increase with lower altitudes.

(6) The reasons for the great differences in the effectiveness of the attacks appear to lie somewhere beyond the figures in this table.

b. Missions 40 and 41. The two attacks chosen for comparison were run within two days of each other and at the same time of the morning, dropped within 7 per cent of the same total bomb tonnage, within 9 per cent of the same tonnage of M69 bombs, and 11 per cent of the same tonnage of M47 bombs (used by Pathfinder).

c. Mission 40 against Tokyo was the first of the great series of incendiary attacks on Japanese cities. Zone 1 was the target and four aiming poings were chosen in the area. The attack started after midnight and lasted almost three hours. Intervalometer settings were at intervals of 50 feet. The planes approached from the southeast against a cross-wind from the southwest. "The bombing sequence planned was from east to west to prevent smoke from obscuring aiming points previously bombed ... " (and, probably, those yet to be bombed). "Bombardiers were instructed to drop bombs on points adjacent to fires previously started." This plan, coupled with the presence of a strong surface wind (Table 29) which helped to disperse the smoke before the inrushing gale had a chance to nullify its effect, enabled about half of the force to bomb visually. As the fire spread, smoke conditions became more static although " ... later aircraft were able to locate heavy smoke." Strike photos indicated that bombardiers were able to follow their instructions. The primary difficulty over the target was

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not so much the visibility restriction as the "... severe turbulence ... due to heat from the fires already started..." which rocked the later ships. A comparison of aiming points and damage sustained suggests that accuracy was excellent. The few bombs which fell short were, in most cases, still within Residential$_1$ areas because of the extent of the highly built-up sections.

d. <u>Mission 41</u> against Nagoya was a night attack planned from information obtained from Mission 40. The target was Zone 1 and three aiming points were selected. Intervalometers were set for 100 feet, to cause, it was thought, more damage. The planes came over Nagoya from the south on an up-wind run; the aiming points were staggered and far anough apart to lessen the possibility of their being obscured by smoke. This precaution was only partly effective: The Tactical Mission Report states that about one-third of the force "...found the aiming points smoke covered and used radar bombing methods..." and that one wing hit its aiming point, ...the other two wings were short." The absence of a strong surface wind contributed to the smoke hazard. A comparison of aiming points with extent of fire damage showed that planes bombed short of the target area, their bombs falling into areas of lower built-upness in some cases and too far to leeward in others to obtain maximum fire spread.

e. <u>Variation in Ground Conditions</u>. Probably the greatest difference in the ground conditions present during the attacks was the velocity of the wind. The wind within the fire area of Tokyo was literally a gale, and few Japanese officials interviewed omitted remarking about it; most of them estimated that the wind velocity just prior to the attack was between 17 and 25 miles per hour and at the height of the fire between 55 and 70 miles per hour. The chief of the fire department estimated the velocity in the heart of the city at 50 miles per hour at 0230 hours. No similar condition existed in Nagoya and the people had no recollection of a strong wind. The following data were obtained from weather stations just outside the fire areas:

TABLE 28

AVERAGE WIND VELOCITY IN MILES PER HOUR

TIME	TOKYO	NAGOYA
0100	15	8
0200	21	9
0300	28	6
0400	24	4

The normal surface wind in Tokyo, therefore, was from two to six times stronger than the wind in Nagoya and about five times as strong at the height of the fire. This undoubtedly was the prime factor in the difference between the effectiveness of the two attacks.

f. Variation in Tactics. The principal difference in the tactics of the two attacks arose directly from the greater smoke hazard which was present during the Nagoya attack, necessitating the premature release of many bomb loads. That, in turn, was due to the relationship of two factors: the heading of the planes and the direction and velocity of the surface wind. In addition, different results were obtained by the bombs which fell short in the two cities because of the difference

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in the size and location of highly built-up areas outside of the target areas themselves.

7. Results of the Attacks against the Two Cities

a. (The following is a reconstruction of the story of the Tokyo fire based on interviews, newspaper accounts and Twentieth AF data.) It is just after one o'clock in the morning and all is quiet. The city is deep in slumber. A few patrol boats are moving in the harbor, and here and there a policeman is awake, seeking to warm his hands over hot coals, for it is chilly this month of March and a crisp, restless wind is sweeping across Tokyo and out over the bay.

Suddenly the air-raid sirens begin their low, dismal moan; then rise in an ever-increasing crescendo until they reach a piercing shriek; the little houses that crowd the city are pervaded with its ominous din. Some of the sleepers awaken quickly, some slowly, others not at all. People run into the streets to catch a glimpse of the low-flying B-29's; they start to gather a few treasures, give up, and crawl into their ludicrous little shelters; or they report to their civilian defense posts. But some sleep on.

The bombs are dropping, sporadically now, for the pathfinders are laying a short direction indicator from Arakawa to Fukagawa. The swish and roar of oil bombs can be heard in many places. Now the lighter bombs begin to drop, almost as steadily as a gentle April shower. There is a pink glow all around, but notice--it is deepening quickly to magenta, to a crimson glare. The wind is certainly getting stronger --and hotter.

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There still isn't any fire right here, but the heat is stifling. Nobody is asleep now. No desultory picking and choosing of belongings. The heat is closing down; it is unbearable. That curtain of flame must be three miles long. Tremendous blasts of wind make it impossible to stand up. It is better to crawl.

The fire is running wild engulfing all in its demoniacal fury. Perhaps the canal...but, no there is fire that way too. It is getting impossible to see anything. This wind. Are those people over there? Those cinders? Is the canal boiling? It is impossible to crawl out through here ...

The fire chief is making a special tour of inspection. He has ordered out all available engines from the districts which are still intact. He starts toward the northeast through Kanda and Shitaya and Asakusa. Parts of tin roof sheeting pelt against his car. It bursts into flame. Fast work extinguishes the blaze and he races on, then back along the river through Mukoshima, Honjo, Fukagawa. The wind must be up to seventy now. Again a fire in his car has to be put out.

Why continue this trip? He has seen all there is to see: fire leaping from building to building, creeping along the ground and through the debris, vaulting fire breaks and canals. Black, charred bodies strewn in the streets. His fire houses and pumping stations are in flames, water hoses dry, fire fighters trapped. The very rivers are near the boiling point. The situation is hopeless--beyond rational thought. Almost sixteen square miles are gone, thousands are dead and more than a million persons are homeless without hope for the morrow.

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b. (The following is a reconstruction of the story of the Nagoya fire based on interviews and Twentieth AF data.)

It is cold in Nagoya but there is scarcely any wind. There has been talk all day about the great disaster in Tokyo. Will Nagoya be next? Is Nagoya ready? Will it be tonight?

One o'clock in the morning. It is about time.

Equipment and personnel have been concentrated heavily around the downtown section. What were those instructions? Confine the fires to previously prepared areas and fight them along their perimeters. Dispatch light equipment and hand pumpers to the windward edges and heavier equipment and the bulk of available man power to leeward. But what is the wind's direction? There doesn't seem to be much. Good! That will keep the fire from spreading.

Here's the alarm. It is tonight. The bombs are dropping now but they're not all landing downtown. Here and there are many small fires. Some are in Nakamura to the west, but that's practically suburban and the houses aren't close together at all; some down in Minami and Atsuta to the south, but those districts are mostly steel and parks and undeveloped land; some in Showa to the east, but there's nothing much to burn over there. Those fires can't do much damage even if the wind rises.

But how about downtown, especially the west ward? Look at that pink glow. The fires are merging but there is no great sweep of flame. The wind is still down. The fire breaks seem to be holding. No use trying to stop that one: Let it burn itself out against the

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field---and that one against the arsenal---and that one against the fire break. The large fires are all in the leeward sections of downtown. Perhaps if all the bombs had landed downtown instead of just some of them ... but they didn't.

What little wind there was has subsided. Everything seems to be under control. Only two square miles gone. Only 600 killed. Nagoya is still sound. What saved it? Its size, the wind, and the inaccuracy of the bombing.

8. Efficiency of Fire Breaks. A good index of the intensity of the fires and the velocity of the winds that drove them along can be obtained from an examination of the efficiency of the fire breaks in the two cities; it should be kept in mind that many of the breaks in Tokyo had not been cleared of debris.

TABLE 29

EFFICIENCY OF FIRE BREAKS IN TOKYO AND NAGOYA*

(Distances in Linear Miles)

	TOKYO			NAGOYA		
	150 ft or over	65-150 ft	Total	150 ft or over	65-150 ft	Total
Total Length	26.3	51.7	78.0	18.1	18.9	37.0
Subjected to Fire	20.6	37.3	57.9	9.2	11.2	20.4
% Subjected to Fire	78.3	72.1	74.2	50.8	59.2	55.1
Fire Stopped**	3.6	2.3	5.9	6.9	3.9	10.8
% Stopped	17.4	6.1	10.1	75.0	34.8	52.9

* Areas examined are the same as for Table 2: Tokyo, 11.8 square miles and Nagoya, 4.98 square miles.

** Fires were considered "stopped" where indenciary damage existed directly on one side of the fire break only. This is, therefore, an assessment of minimum efficiency because fires on both sides were often caused by bombs falling on both sides and not by fire spread.

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The efficiency of the Nagoya fire breaks was about five times as great as that of the Tokyo fire breaks. No simon-pure mathematical relationship could be set up between efficiency and wind velocity, wind direction, width of break and size of the fire because the variables were too difficult to ascertain. It is evident, however, that there was a direct relationship between effectiveness of fire breaks and the velocity of the wind. (Note that the wind in Tokyo was about five times as strong as that in Nagoya at the height of the fires.) It is also evident that the effectiveness of fire breaks decreased with an increase in the intensity of the heat of the fire and with a decrease in the width of the break. A study of the effects of wind incidence to fire breaks was almost impossible because of the complex nature of wind directions in a fire area.

9. Damage to the Two Cities. The attack on Tokyo damaged 15.8 square miles while that on Nagoya damaged 2.1 square miles. (Figures No. 18 and 19). The total damage from all attacks on Tokyo totalled 69.4 square miles, on Nagoya, 12.0 square miles. These figures, however, do not give the entire picture of the accuracy or efficiency of the attacks because many other factors are omitted.

10. Accuracy of Attacks. At least an indication of the accuracy of the two attacks can be gained by an examination of the percentages of the zone (the target itself) damaged:

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TABLE 30

PERCENTAGES OF ZONES DAMAGED

	TOKYO	NAGOYA
Area of Zone in Square Miles	11.80	5.71
Damage in Square Miles	8.09	1.72
Percentage Damaged	68.6	30.1

It must be kept in mind, however, that the character of the targets differed considerably. The planes over Tokyo approached the wide base of a rectangle while those over Nagoya approahced the thin apex of a triangle of half the area. Actually, no quantitative assessment of bombing accuracy could be made.

11. Efficiency of Attacks. An approximation of the efficiency of the attacks can be gained by an examination of the percentage of total built-upness damaged for every thousand tons of bombs dropped on the cities. This method takes into consideration the amount of combustible material available. For the Tokyo attack, every thousand tons of bombs dropped damaged 9.48 square miles or 5.8 per cent of the built-up area of the city; for the Nagoya attack, every thousand tons of bombs dropped accounted for 1.14 square miles of damage or 2.9 per cent of the total built-up area. The Tokyo attack, therefore, was almost exactly twice as efficient as the Nagoya attack when computed on this basis. The same information for all major attacks is listed in Table 32. It can be seen from this that Missions 40 and 41 were extreme examples of efficiency difference since, for all attacks, every thousand tons

TABLE 31

DAMAGE FROM MAJOR ATTACKS

	AREA IN SQ MI		SQ MI DAMAGED		PERCENTAGE DAMAGED		SQ MI DAMAGED PER 1,000 TONS DROPPED		PERCENTAGE DAMAGED PER 1,000 TONS DROPPED	
	Tokyo	Nagoya	Tokyo	Nagoya	Tokyo	Nagoya	Tokyo	Nagoya	Tokyo	Nagoya
Residential$_1$	22.50	4.98	17.10	3.76	76.0	75.5	1.36	.38	5.4	7.6
Residential$_2$	53.84	12.78	21.53	3.75	40.0	29.3	1.72	.38	2.8	3.0
Residential$_3$	63.89	12.65	25.56	1.30	40.0	10.3	2.04	.13	2.8	1.0
Manufacturing	12.45	6.49	2.12	2.06	17.0	31.7	.17	.21	1.2	3.2
Mixed	7.39	1.97	2.44	0.96	33.0	48.7	.19	.10	2.3	5.1
Transportation	1.67	0.22	0.17	0.02	10.2	9.1	.01	.00		
Storage	2.34	0.64	0.49	0.12	20.9	18.8	.04	.02		
Entire Built-up Area	164.08	39.73	69.41	11.97	42.3	30.1	5.53	1.22	3.4	3.1

of bombs dropped on Tokyo damaged 5.53 square miles or 3.4 per cent of the total built-up area while every thousand tons of bombs dropped on Nagoya damaged 1.22 square miles or 3.1 per cent of the total built-up area. It is also indicated that the efficiency against Nagoya's residential areas was better than that against Tokyo's residential areas. In other words, the efficiency of the attacks against the two cities was almost the same when it is based on the percentage exposed and burned.

12. Casualties in the Two Cities

TABLE 32

CASUALTIES

	ALL ATTACKS		MISSIONS 40 AND 41	
	TOKYO	NAGOYA	TOKYO	NAGOYA
Dead	95,972	7,724	83,793	602
Injured	70,475	10,533	40,918	1,238
Totals	166,447	18,257	124,711	1,840
Percentage of population	3.3	1.6	2.5	negligible

The difference in population densities, areas involved, and preparedness were responsible for the higher casualty rate in Tokyo.

13. Conclusions

a. On the basis of percentage of built-upness damaged per 1,000 tons of bombs dropped, the 9 March Tokyo attack was about twice as effective as the 11 March Nagoya attack, and the efficiency of all major attacks against Tokyo, taken as a whole, was about equal to that of those against Nagoya.

b. The 9 March Tokyo attack was more effective than the 11 March Nagoya attack for the following reasons, listed in the approximate order of their importance:

(1) The wind was much stronger, causing greater fire spread, and it came from a quarter which reduced the smoke hazard to below that which existed during the Nagoya attack.

(2) Tokyo and its target area were larger and consequently easier to hit. In addition, bombs which fell short of the Tokyo target area fell in highly built-up sections of the city. The resulting fires in Tokyo were larger and hotter, causing increased fire spread, and making them more difficult to approach for control purposes.

(3) Tokyo was more vulnerable than Nagoya because its layout was more conducive to a conflagration, its population density was greater, its fire department was less efficient and extensive, its water system was not so good, and its fire breaks were only partly completed and not so extensive.

G. CONCLUSIONS AND COMMENTS

1. General. This report attempts to answer some of the questions on the effectiveness of the incendiary program against the Japanese homeland, particularly with respect to bombs, tactics, and characteristics of the targets. It does not answer all fire problems. It is

intended rather to show that data are available for further study in Survey fire reports where more details can be found. Where adequate data were obtained and the results were fairly conclusive, they are so indicated. In a small way, therefore, this report confirms or denies the validity of certain general policies of how, when, and where attacks should have been directed.

2. The Incendiary Program. B-29 planes flew over the Japanese homeland in 79 major incendiary missions involving 13,365 sorties over targets, and dropped 93,000 tons of incendiaries and 650 tons of high explosives and fragmentation bombs; about 175 square miles of the hearts of cities sustained nearly 100 per cent building damage. Another 20 minor missions dropped 12,000 tons to damage four square miles more.

3. The Cost. The results were not obtained cheaply. About 550 tons of bombs were expended per square mile of nearly 100 per cent damage.

4. Planning

a. Operational Considerations. In general, the choice of targets, bombs, and tactics was not sufficiently controlled to permit enough data for definite conclusions, since it was the policy of operations personnel to get the greatest amount of damage possible from attacks by using whatever information and material were available at the time. Their choice, therefore, was varied because they knew that less damage would be obtained under certain conditions. A certain type of bomb, for example, might be used against a target (and yield less damage than others), because the bomb was the only one available for that specific attack. An assessment of the effectiveness of that particular bomb, consequently, shows lowered efficiency and only a more detailed study could evaluate the influences of such anomalies.

b. Decisions. The decisions relating to target selection were generally good. Combustibility, war industries, transportation, size, and radar identification were criteria. It was found, however, that combustibility and size were almost always analagous because the extent of built-upness was in practically direct proportion to the size of the city, the density of built-upness was in direct proportion to its extent, and the resultant was equal to vulnerability (since the percentage of noncombustible structures in any city never exceeded ten per cent). Aiming points, therefore, could have been chosen purely on the basis of built-upness with little regard to construction or occupancy.

c. Attacks on Small Cities. The policy of attacking small cities to discourage the dispersal of industrial facilities was not completely effective, for it was found that new and re-located industries for critical items were set up outside city centers and in the country.

d. Use of Large Incendiaries. The policy of using large incendiary bombs to start identifying fires for later attacking planes did not show, in the extent of damage, any advantages. Attacks not employing this technique caused about the same amount of damage.

e. Non-use of High Explosives. The decision to use no high-explosive bombs on Japanese cities resulted, at least partly, from the operational difficulties involved in placing both high-explosive and incendiary bombs on the same target areas. The evidence suggests that high-explosive bombs of the proper size and fusing might have increased the efficiency of the incendiary attacks provided they could have been effectively distributed over the target areas.

revealed by studies on the extent of damage and the examination of undamaged targets.

f. Effect of Weight of Attack. The weight of the attack, after a 500 ton minimum, apparently overwhelmed fire defenses, but had little influence on the possibility of starting fire storms, conflagrations, or of obtaining bonus results of any kind. The latter were more the resultants of factors beyond the control of planners.

g. Urban-Area Attacks. The over-all policy of attacking urban areas to involve industrial clusters and large plants was not proved to be feasible because the latter were not appreciably damaged by domestic building exposure fires; less than 25 per cent of them were fired, and these probably by the bombs themselves. The firing of urban areas to involve small home shops and industries intermixed with domestic buildings, on the other hand, was profitable.

h. Variation in Effects of Equal Weights of Bombs. Japanese targets showed a variation in effects of equal weights of bombs of from one to seven. These differences are accounted for mainly by the diversities in physical ground features and meteorological conditions.

i. Cost of Damage. The cost of damage per unit weight of fire bombs dispatched was greater for Japan than for Germany, principally because a lower ratio of bombs hit Japanese targets, especially unburned portions, and larger incendiary bombs and heavier bomb clusters were used.

5. Target Characteristics

a. Built-upness. The most important ground feature of urban-area targets was the degree of built-upness of the densely populated residential-commercial core (10 to 35 per cent of the city area) which averaged 45 per cent build up. The moderately dense area which usually constituted about half of the city was 31 per cent built up. The remainder was built up from about 14 to 38 per cent. The densely built-up areas were almost always the most vulnerable. The mixing of residential and industrial buildings of a given built-upness decreased the fire vulnerability of the former and increased that of the latter.

b. Typical Vulnerable Structures. The typical Japanese dwellings, home shops, and commercial frame buildings constituted about 90 per cent of the total structures. They were highly fire vulnerable because of the combustible material present and especially because of the large amount of light wood surface exposed. The tile roofs were effective in preventing fires from flying brands, but long eaves counteracted this effect by catching brands and by acting as heat traps.

c. Noncombustible Structures. Noncombustible structures were vulnerable only in proportion to the amount and combustibility of their contents. Modern earthquake-resistant buildings were practically invulnerable from direct incendiary bomb attack, but were highly vulnerable to damage from exposure fires because of their combustible interior finish and dearth of good exposure-protective devices. Some Japanese "godowns" were vulnerable because of their unprotected eaves.

d. Fire Breaks. Natural and man-made fire breaks varied in effectiveness with the direction and intensity of the wind. Of the 80 linear miles of breaks (with damage on one or both sides) studied, fire

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stopped on one side of those 150 feet or more wide 17 per cent of the time, and on one side of those between 65 and 150 feet 6 per cent of the time under conflagration conditions (Tokyo). Under non-conflagration conditions (Nagoya), fire stopped on one side of the larger breaks 75 per cent of the time, and on one side of the smaller breaks 35 per cent of the time. (These figures represent minimum efficiency, since the places where bombs fell on both sides of the fire breaks would not be identified.) Fire breaks were naturally rendered ineffective when bombs were dropped on both sides. Some breaks, 20 to 50 feet wide around important buildings, were found effective in preventing fire spread principally because of the low vulnerability of the buildings themselves.

e. Fire Fighters and Equipment. The Japanese were poorly prepared to fight large fires. Their training, equipment, plans and coordination were all bad. The water supply was inadequate in pumping and reservoir capacity, and the individual hand equipment was heavy and poorly designed. Hand buckets were the most useful pieces of equipment available; static tanks were of value if located outside the fire perimeter. In spite of its shortcomings, fire fighting was effective around the fringe of a fire, especially if the area were isolated, small, and in a sparsely built-up location.

f. Vulnerability of Pumping Stations. The common practice of placing electrically-operated water pumping stations in combustible buildings made the water supply especially susceptible to failure. In three of six cases studied, the building or supply lines failed

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early in the attack.

g. Effect of Weather Intelligence. Better weather intelligence (if possible, from the urban area itself) might have doubled or even tripled the damage inflicted, since the attackers would have known exactly when to strike for optimum meteorological conditions.

h. Effect of Wind. Wind was found to be the most important meteorological factor, and probably the third most important factor of any kind influencing the extent of damage. Fire, smoke, heat, and vapors were swept ahead. Fire fighting, it is true, was assisted on the windward sides, but impeded on the leeward. Much of the damage due to the 9/10 March Tokyo attack can be attributed to the 28-mile-per-hour wind.

i. Effect of Temperature and Humidity. Temperature and humidity had less effect. The high moisture content of the wood in Japanese structures influenced the high density of bombs needed to establish initial fires. Attacks made on cities where it had been raining or snowing prior to or during the attack were slightly less efficient than the average of other attacks.

6. Tactics

a. Daylight Attacks versus Night Attacks. Daylight attacks produced 27.5 per cent more damage per ton of bombs than night attacks, even though they were flown at higher altitudes and carried 20 per cent less bomb load.

b. Multiple-Aiming-Point Attacks versus Single-Aiming-Point Attacks. Attacks in which multiple aiming points were used produced an

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average of 11 per cent more damage per ton of bombs than attacks with single aiming points. This fact can be attributed partly to the effects of bomb spillage between aiming points in the former situation, which straddled vulnerable areas.

c. Effect of Target Size. Large targets sustained more damage than small targets because of bomb spillage cited in paragraph b above.

d. Bomb Density. Although the 800 tons of bombs dispatched were to give a planned density of 225 tons per square mile, it was estimated (in the limited data of four calculations) that a slightly higher density was actually achieved, and that a ground density of 150 to 200 tons per square mile would have been more efficient. When more than 500 tons per aiming point were dispatched, the efficiency actually began to decrease.

e. Time over Target. The number of factors present in the attacks was so great that it overshadowed the influence of duration of time over target; attacks of less than 60 minutes, for example, were found about as effective as those of 120 minutes. There was, however, a slight advantage when the bomb delivery rate exceeded 20 tons per minute compared to that of less than 10 tons per minute.

f. Intervalometer Spacings. Attacks using intervalometer spacings of less than 50 feet were not as efficient as those using settings of more than 50 feet.

g. Axis of Attack. The axis of attack was an important factor, but available data do not warrant definite conclusions. In general, more damage was sustained when bombs were dropped across or with

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the wind rather than against it. Still more important was the location of densely built-up areas in relation to the wind and center of impact.

7. Bombs

a. Use of High Explosives. The addition of high-explosive bombs up to 10 per cent of the load had no effect on the efficiency of the attack.

b. Anti-personnel Agents.

(1) The use of T4E4 fragmentation bombs and air bursting high explosives in the amounts used was ineffective as anti-personnel agents.

(2) The white phosphorous anti-personnel agent of the M74 bomb was generally ineffective, principally because fires were not fought where it fell.

(3) The explosive nose of some M50 bombs was an effective anti-personnel agent.

c. Efficiency of Clusters. The excessively heavy weight of the E46 cluster, designed primarily to give increased accuracy in high-altitude attacks, decreased the efficiency of medium-level attacks for which lighter clusters could have been used.

d. Fire Raisers.

(1) Both the six-pound M69 and ten-pound M74 oil-gel bombs were highly effective in starting fires in Japanese domestic and commercial frame buildings; the latter was found to be slightly superior on a weight basis (according to data from only a few M74 incidents

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compared with those of an adequate number of M69 incidents).

(2) Only the M50 bomb was found deficient as a fire raiser and the easiest of all incendiary bombs to extinguish. Apparently, however, enough of these bombs were dropped to start fires in inaccessible places, bringing the over-all efficiency up to that of other small bombs.

e. Perforation and Penetration

(1) The hundred-pound M47 bomb and the four-pound M50 bomb were unable to perforate reinforced-concrete buildings.

(2) The M50 bomb exhibited an unexpected ability to penetrate four feet of soft earth and perforate cast-iron pipes. The average penetration of 34 hits on concrete roofs, however, was only 1.5 inches.

(3) The M47 bomb easily penetrated Japanese dwellings and burst 6 to 12 feet below the point of impact.

(4) The M69 and M74 bombs were found to have the correct amount of penetration to perforate Japanese domestic roofs. Some continued through "tatami" mats and floors.

(5) The use of the 500-pound M76 bomb on city areas containing reinforced-concrete buildings was not profitable. So few bombs hit the buildings, and the area of fire damage in these buildings was so small, that

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the damage was not commensurate with the weight of the bomb. It was able to perforate a nine-inch-thick concrete roof and one floor, where it exploded before piercing the next floor below. Corrugated-iron or asbestos-covered roofs did not activate the bomb fuze.

f. Malfunctions. Heat from fires destroyed many malfunctioning bombs, rendering most figures unreliable. The Japanese indicated duds as follows: 5 to 10 per cent for the M69, M47, and M74; none for the M76; and up to 20 per cent for the M50. Most of the latter cases were due to the bomb's stiff firing pin and to mechanical injury.

8. Effects.

a. Degree of Damage to Buildings. Combustible buildings usually burned completely. Noncombustible and fire-resistive buildings sustained damage from the firing of combustible contents and interior trim. There was less salvage value to the contents of Japanese combustible and fire-resistive buildings than there was for similar German buildings because of the higher combustibility of both the Japanese structures and their contents. Noncombustible buildings and contents sustained about the same damage under similar conditions in the two theatres.

b. Weather. Weather was again found to be a serious source of further damage to machinery and equipment after the fire.

c. Protective Devices.

(1) Fire doors were rare, but the well-constructed ones in use stood the test of fire quite well; the most

common cause of failure was the lack of automatic closing features and inferior hardware. Fire shutters were generally constructed of sheet iron, sometimes of reinforced concrete, and stood up fairly well; their more liberal use, especially more than one floor above the roof of an exposing building, would have saved many buildings. Wire-glass windows failed often because of severe exposure to fires.

(2) Automatic sprinkler systems were uncommon and usually failed because of lack of water. Standpipe systems were common in concrete buildings but few were used for protection; those that failed were again without adequate water.

(3) Safes were in exceedingly common use but were of inferior material and workmanship. Failures of two-inch-thick, insulated safes were common, especially with earth, clay, sand or concrete insulation fills; no six-inch, insulated safes were reported burned out regardless of the type of fill.

d. Transportation. Urban-area attacks and spill-overs were the main causes for passenger car losses of 12.3 per cent, locomotive losses of 5.3 per cent, freight car losses of 3.1 per cent, substantial street car and power-line pole losses, and a few shipping facility losses.

e. Casualties

(1) Incendiary attacks killed about 165,000 persons (1.3 per cent of the population of the cities bombed), injured 200,000, and dehoused 8,000,000. Almost two tons of bombs were required to kill one person.

(2) Incendiaries were slightly better casualty agents than high explosives.

f. Morale. The morale of the people and their willingness to fight fires decreased with successive attacks and with time.

g. Fire Storms and Conflagrations. When at least a square mile of a Japanese city was afire during certain prevailing meteorological conditions, fire storms or conflagrations sometimes developed. Both were highly effective damage and casualty agents, the conflagration being several times more so than the fire storm.

(1) Fire storms required light winds, clear weather, and many individual fires in densely built-up residential area. A "pillar" or "thermal" was formed over the city, causing high winds around all sides of the fire perimeter and, sometimes, rain on the leeward side when the thermal hit a stratum of cold air.

(2) Conflagrations required high surface winds striking the thermal, so that it came closer to the ground and encouraged fire spread.

(3) Neither conflagrations nor fire storms occurred during rains or where the rain fall had been excessive prior

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to the attack.

h. Fire Spread.

(1) Fire spread (those burned areas outside of which bombs fell) was about 25 per cent under normal and fire-storm conditions. Under conflagration conditions (Tokyo) fire spread was 100 per cent.

(2) In one city fire spread was responsible for 82 per cent of the damage in residential zones of 42 per cent average built-upness, compared to 16 per cent fire spread in residential zones of 12 per cent average built-upness. (Both were subject to fire spread alone). In the same city, fire spread across fifteen-foot open spaces 84 per cent of the time and across hundred-foot open spaces 46 per cent of the time.

(3) In another city, fire spread across fifteen-foot open spaces 80 per cent of the time to windward, and 98 per cent of the time to leeward; across hundred-foot open spaces 36 per cent of the time to windward and 42 per cent to leeward.

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CHAPTER IV

DAMAGE TO MACHINERY

A. SUMMARY

1. Extent of Machine Damage. Studies on Japanese industrial targets confirmed the fact that machinery is difficult to damage with aerial weapons, even when large high-explosive bombs are employed. It will be seen from Table 1 that, generally speaking, machine damage averages one-half of building damage.

2. High-Explosive versus Atomic Bomb. The atomic bomb was effective as an agent in disrupting manufacturing facilities. In contract to the effects of the high-explosive bombs which damaged machinery primarily by direct action (blast, fragments, earth shocks), the atomic bomb caused damage almost entirely by its indirect effects, primarily in the form of debris. MAE's for machinery damage in Nagasaki were as follows:

a. For machinery in wood-frame structures: 1.68 square miles

b. For machinery in steel-frame structures: 0.872 square mile

c. For machinery in reinforced-concrete structures: 0.553 square mile.

B. GENERAL INFORMATION

1. Scope of Study. The Physical Damage Division in Japan studied, among other things, damage to machinery by:

a. High-explosive bombs of various sizes

b. Incendiary bombs

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c. Atomic bombs

This report summarizes the damage caused by these three types of weapons.

2. Objective of Strategic Bombing. The objective of attacking industrial plants with aerial weapons is to paralyze production for the longest possible time. If an attack succeeds in damaging beyond repair a large proportion of either the machinery or equipment (plant utilities, small tools such as jigs, fixtures) in a plant the objective of the attack has been accomplished. Much effort has been put forth to create the most effective weapon for destroying the enemy's industrial potentialities. These efforts culminated in the creation of the atomic bombs which exploded above Hiroshima and Nagasaki in Japan.

3. Categories of Damage. Categories used to describe machine tool damage are:

Total Damage - Damaged beyond repair and of no further value except as scrap.

Heavy Damage - Damaged to such an extent that the machine cannot be repaired by the plant maintenance crew.

Slight Damage - Damage can be repaired by plant maintenance crew.

C. DAMAGE ANALYSIS

1. High-Explosive Bombs

a. Vulnerability of Machinery. Studies of Japanese industrial targets clearly reveal the fact that machinery is extremely difficult to destroy even when large bombs (1,000 pounds and above) are employed

(Photos 1 and 2). A much greater concentration of bombs is required to damage all the machines in a steel or reinforced-concrete building than is needed to damage structurally the entire building. Generally, collapsing structural members in steel-frame buildings are ineffective in producing serious damage to machinery unless some other damaging agent is also present. Similarly, debris, even that from damaged brick and reinforced-concrete buildings, rarely produced unrepairable or heavy damage, although it may cause slight damage over a wide area.

2. Heavy Machines. Very heavy machines are more effectively damaged by bombs which crater than by bombs which detonate in the air (Photos 3 and 4). Unrepairable or heavy damage to such machines is usually limited to machines whose beds are broken by shock or blast, and debris from bombs which explode in close proximity to them.

3. Light Tools and Machines. Light tools and machines are more vulnerable to blast and fragments than are heavy machines and are more effectively attacked with non-cratering bombs. Blast alone is generally less effective than fragmentation in producing machine tool damage except possibly in the case of medium-sized machines, such as lathes and milling machines.

4. Effect of Small Bombs. It appears that light machines and equipment can be most effectively attacked with relatively small bombs, for example, the 500-pound bomb (Photos 3 and 4) which provides a dense concentration of fragments around a large number of points of detonation.

5. Auxiliary Value of Debris. Although debris cannot be relied on as an agent for causing heavy damage, it nevertheless assists large,

light-case (blast) bombs.

f. Blast Effects. The effects of blast alone, although severe near the point of detonation, are not sufficiently widespread to make even 4,000-pound light-case bombs as effective against machinery as the small bombs on a tonnage basis.

g. Insufficient Information. Sufficient information on the effects of individual bombs is unavailable to make possible the preparation of graphs of the probable effects of the bombs to be used in the preparation of MAE's.

h. Effect of Large Bombs. It should be emphasized that large bombs (1,000-pound and over) are capable of seriously impeding production in industrial plants even if they do not damage a large proportion of the machinery. This is accomplished by damaging plant utilities and equipment such as furnaces, cranes, and gas producers. Blast from bombs is also effective in damaging small tools (jigs, fixtures) and, as these are vital to any industry and are often exceedingly difficult to replace, the importance of their loss should not be underestimated.

2. Incendiary Bombs. A large variety of types of incendiary bombs, ranging in size from 4 pounds to 500 pounds was used on industrial targets in Japan. As agents for directly damaging machinery they were not so effective as high-explosive bombs, for their effectiveness was largely dependent upon the combustibility of the buildings and their contents. In plants where machines were damaged by fire, it was usually evident that the machines had been in contact with flames from debris or other

combustible material. However, although the ability of the incendiary bombs to destroy machines by direct action was small, there were some instances in which the electrical equipment associated with machines (motor, wiring, switchboards) was burned out by direct contact with an incendiary bomb.

3. Atomic Bomb. In contrast to the effects of conventional high-explosive bombs in which most of the damage to machine tools was caused by direct action (blast, fragments, earth shock), the atomic bombs caused damage almost entirely by its indirect effects, principally in the form of debris hurled against the machines (Photos 99 - 101). This debris consisted of shattered portions of the buildings which housed the machines. Although there is in attacks with high-explosive bombs an important relation between the magnitude of structural damage to a building containing machine tools and the amount of damage to the machines themselves, this relation is much more marked in attacks with the atomic bomb, that is, it was not unusual to find instances where a high-explosive bomb cratered inside a large building and caused considerable damage to machine tools by direct action without causing more than minor damage to the building. Such a case was almost impossible in atomic-bomb attacks because the machinery damage was largely dependent on the degree of damage to the structures.

a. Mean Areas of Effectiveness. Table 34 which accompanies this report gives the number of machines damaged in Nagasaki, together with the severity of the damage and its cause. From these figures graphs

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have been plotted and MAE's calculated for the three major types of buildings used for housing machinery in Nagasaki, by the method devised by the RE8 section, British Ministry of Home Security, and described below.

a. Concentric circles were drawn around GZ (ground zero, i.e., the vertical projection on the ground of the bomb's point of detonation). The fractions of damage in the annuli were calculated by dividing the sum of the totally damaged and heavily damaged machines by the total number of machines exposed. These values were then plotted as shown in Figures 1 to 4. MAE's were calculated by using the product of these fractions and the area of the annuli. The product-sum so obtained gives an estimate of the area over which all machines may be expected to be damaged.

3. Machine Damage. The industries in Hiroshima situated within the damaged area were all small and relatively unimportant. There were insufficient examples available to plot graphs for damage and for computation of MAE's. However, the degree and causes for machinery damage were identical to those in Nagasaki; therefore, the following, although elaborating on the description of damage in Nagasaki, also includes the damage in Hiroshima.

a. Examination of the graphs, Figures 1 to 4, shows that machinery in wood-frame structures (Photos 7 and 8) was most vulnerable to the effects of the atomic bomb. It may be questioned why the number of machines damaged in wood structures near GZ was so high. The explanation for this lies in the fact that all these machines were belt driven from overhead shafts. The buildings received the blast as an almost vertical force and collapsed directly upon the machines causing the shafts to fall upon the machines with great velocity, thereby overturning or fracturing them.

b. Machine tools in steel-frame buildings (Photos 9 to 11) suffered less damage than the machines in other types of buildings, principally because the debris from destroyed roofing and siding material was too light to cause serious damage. At considerable distances from GZ, where the vertical component of the blast pressure had decreased a great deal and the horizontal component had become large, the horizontal force exerted by the blast was sufficient to distort the steel frames, especially the lighter ones, in a horizontal direction, overturning or fracturing the machines within them. This factor contributed to the damage in steel-frame buildings so that as the distance from GZ increased the fraction of the machines damaged in steel structures decreased at a rate not appreciably different from that shown by the graph for damage in wood structures.

c. Machine tools in reinforced-concrete buildings (Photos 5 to 7) near GZ suffered almost as much damage as did those in wood structures, but the damage in the reinforced-concrete structures decreased farther away from GZ. Two thin-shell, industrial-type, reinforced-concrete structures suffered part collapse at a considerable distance from GZ, the heavy debris from the roof causing considerable damage to the machines therein. These buildings were not, however, typical of the reinforced-concrete buildings in the city. (They were included in the MAE. If excluded, MAE would be 0.40 square mile.

c. Fire and Blast. Although, as has already been stated, debris was the major agent for damage to machinery in atomic bomb attacks, it should be emphasized that a combination of fire (Photos 109 - 112) and blast also contributed to the over-all damage. The damage caused by fire was, however, entirely dependent on the combustibility of the buildings in which the machines were located and was chiefly confined to wood-frame buildings. The fire hazard to machinery in a modern industrial plant in the United States would be small, even negligible in certain types of industry.

d. Blast. Although only a few machine tools sustained damage as a direct result of blast alone, the effects of it were widely and plainly evident on equipment such as furnaces, cranes, plant utilities, and small tools, all of which perform important functions in industrial plants. The graphs, Figures 27 - 30, furnish an idea of the area in which such equipment was damaged, for the damage to them was confined to the same area as that in which machine tools were damaged, although the fraction of damage by blast to equipment was at all points 25 per cent higher than that for machine tools.

e. Weather. The effects of the elements on machinery exposed by the damaging of buildings must be considered in the over-all picture of the damage. Of all the machines damaged in Nagasaki, 54 per cent suffered damage from exposure, largely in the form of rusted sliding surfaces. The longer a machine was exposed the deeper the corrosion penetrated the sliding surfaces, often resulting in the complete ruin of the machine.

F. CONCLUSIONS

Certain conclusions can be drawn from a comparison of the effects of high-explosive bombs and atomic bombs. Although the damage to machine tools by high-explosive bombs was dependent somewhat upon the type of structure in which the machines were housed owing to the varying tendencies of structural types to furnish debris as a damaging agent, the most reliable damaging agents of high-explosive bombs were the direct effects (blast, fragments, shock). These agents were effective in causing serious damage within a limited radius from the points of detonation so that a large number of hits on a single plant was required to damage a sufficiently large portion of its machinery and equipment to paralyze production. The atomic bombs paralyzed production not by damaging a large fraction of either the machinery, equipment, plant utilities, or small tools, but by damaging to a greater or lesser degree a substantial portion of each of them. This was true of all plants within the area of heavy damage, which was, of course, different for each building type so that the effects of the bomb were determined by the types of industrial structures within its radius of effectiveness. There can be no doubt about the superiority of the atomic bomb as a weapon for disruption of production in industrial plants.

G. PROTECTIVE MEASURES

1. Blast Walls. Protective measures in the form of blast walls were widely used in the industrial plants in Japan. Although the Germans considered loose brick walls more effective than reinforced-concrete

walls, either pre-cast or poured in situ, the Japanese employed only the following types:

1. Reinforced-concrete - pre-cast, hollow type Photo 113
2. Reinforced-concrete - poured walls Photos 114 - 115
3. Wooden earth-filled types Photo 116
4. Steel frames and steel plates Photos 117 - 119

All of these types proved to be effective against conventional-type bombs as well as the atomic bomb, the wood types being the least effective.

5. The pre-cast-concrete type gave excellent protection against the atomic bomb in Nagasaki. It protected vulnerable machines from the direct blast effects of the atomic bomb and shielded them from collapsing members of the heavy steel structures.

TABLE 33

COMPARISON OF BUILDING AND MACHINE TOOL DAMAGE

LIGHT MACHINE TOOLS

TYPE OF CONSTRUCTION	TARGET AND REPORT NUMBER	BLDG NO	PERCENTAGE OF BLDG DAM	PERCENTAGE OF MACH DAM	REMARKS
Steel-frame structures	Mitsubishi Heavy Industries, Ltd. No. 6 works, Shizuoka PDD Report 71	1	29	13	Total: 13 2,000-lb GP bombs of which 9 were direct hits and 4 were near misses (CB)*
	Kawanishi Aircraft Co. Ltd., Takarazuka PDD Report 73	1	49	35	Total: 11 1,000-lb GP - DH - (CB)
	Sumitomo Light Metals Works, Ltd. Osaka PDD Report 72	43	100	44	Total: 1 1,000-lb HE (CB)
		77	87	50	Total: 1 2,000-lb GP - (CB) - DH 3 2,000-lb GP - (AB) - DH
	Osaka Army Arsenal, Osaka PDD Report 73	59	80	17	1 2,000-lb GP - DH - (AB)
	AVERAGE		68	32	5 incidents, 29 bombs
Load-bearing Masonry	Osaka Army Arsenal, Osaka PDD Report 73	60	85	53	1 1,000-lb GP - DH - CB 2 2,000-lb GP - DH - CB 1 2,000-lb GP - DH - AB
		82	50	18	1 2,000-lb GP - DH - (CB)
		93	100	70	11 2,000-lb GP - DH - (CB)
	AVERAGE		78	47	3 incidents, 16 bombs

TABLE 33 (continued)

COMPARISON OF BUILDING AND MACHINE TOOL DAMAGE

HEAVY MACHINE TOOLS

TYPE OF CONSTRUCTION	TARGET AND REPORT NUMBER	BLDG NO	PERCENTAGE OF BLDG DAM	PERCENTAGE OF MACH DAM	REMARKS
Steel-frame structures	Sumitomo Light Metal Works, Ltd. Osaka PDD Report 72	42	100	36	2 DH-1NM-4,000-lb HE (CB)
		51	97	39	7 CR-5AB-4,000-lb HE (DH)
		58	38	17	3 CR-3AB-4,000-lb HE (DH); 1 DH-4NM-4,000-lb HE (CB)
		64	82	30	6 DH-4,000-lb HE (AB)
		74	60	50	5 4,000-lb HE (AB)
		77	87	40	2 4,000-lb HE (CB); 4 4,000-lb HE (AB)
	Osaka Army Arsenal, Osaka PDD Report 73	28	95	44	1 2,000-lb HE (low order)
	AVERAGE		80	38	7 incidents
Load-bearing Masonry	Osaka Army Arsenal, Osaka PDD Report 73	61	46	22	5 2,000-lb GP (CB); 3 2,000-lb GP (AB); 1 1,000-lb GP (CB)
	AVERAGE		46	22	1 incident

* DH--Direct Hit
NM--Near Miss
CB--Cratering Bombs
AB--Non-crater bombs (Air Burst)

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TABLE 34

DEGREE AND CAUSES OF DAMAGE TO MACHINE TOOLS AT NAGASAKI

	Wood-Frame Structures	Steel-Frame Structures	Reinforced-Concrete Structures
Maximum distance (ft) from GZ that machine tool damage was observed	6500	5600	4700
Percentage of the total No. of machine tools which sustained damage within the above distances	95% (TD-13% (HD-39% (SD-48%	20% (TD-20% (HD-20% (SD-60%	36% (TD-33% (HD-21% (SD-46%
Distribution and Cause of Damage to Machine Tools			
Machine tools damaged by fire	10% (TD-38% (HD-48% (SD-14%	3% (TD-100% (HD- 0% (SD- 0%	9% (TD-77% (HD-23% (SD- 0%
Machine tools damaged by debris	26% (TD-15% (HD-77% (SD- 8%	70% (TD-25% (HD-28% (SD-47%	80% (TD-32% (HD-20% (SD-48%
Machine tools damaged by elements	54% (TD- 0% (HD-15% (SD-85%	27% (TD- 0% (HD- 0% (SD-100%	11% (TD- 0% (HD-29% (SD-71%
Machine tools damaged by blast and combination effects	10% (TD-59% (HD- 9% (SD-32%	0	0

TD - Total Damage
HD - Heavy Damage
SD - Slight Damage

These figures include damage caused by exposure to the elements.

TABLE 35

NAGASAKI

MAE'S OF ATOMIC BOMB FOR MACHINERY

Dist from GZ (ft)	Wood-frame Structures		Steel-frame Structures		Reinforced-concrete Structures	
	F	FA	F	FA	F	FA
500	.52	.52	.48	.48	.48	.48
1,500	.46	1.38	.38	1.14	.38	1.14
2,500	.40	2.00	.29	1.45	.28	1.40
3,500	.34	2.38	.21	1.47	.19	1.33
4,500	.27	2.43	.16	1.44	.10	.90
5,500	.21	2.31	.10	1.10	0	0
6,500	.15	1.95	.05	.65	0	0
7,500	.09	1.35	0	0	0	0
8,500	.03	.51	0	0	0	0

$\Sigma FA = 14.83$	$\Sigma FA = 7.73$	$\Sigma FA = 5.25$
$MAE = \Sigma FA \times \pi \times 10^6 =$	$MAE = \Sigma FA \times \pi \times 10^6 =$	$MAE = \Sigma FA \times \pi 10^6 =$
$14.83 \times \pi \times 10^6 = 46.6 \times 10^6 =$	$7.73 \times \pi \times 10^6 = 24.3 \times 10^6 =$	$5.25 \times \pi \times 10^6 = 16.5 \times 10^6 =$
46600M sq ft	24300M sq ft	16500M sq ft
1,007 Acres	558 Acres	378 Acres
1.68 sq mi	.872 sq mi	.59 sq mi

MAE'S FOR STRUCTURES

7.00 sq mi	3.27 sq mi	.64 sq mi

CHAPTER V

DAMAGE TO UTILITIES

A. SUMMARY

1. Scope. In the study of industrial targets in Japan by Physical Damage teams, the main utility information gathered was that concerning electric, water, gas and sewerage systems.

2. Vulnerability of Utilities. Utilities as a whole were found to be vulnerable to air attacks. They sustained considerable damage which in many cases retarded plants' production capacities although the processing machinery was intact.

3. Effective Types of Bombs. High-explosive, incendiary, and atomic bombs were used with good results in attacks on Japanese industries. Although sufficient data were not available to permit calculations of Mean Areas of Effectiveness (MAE) for high-explosive and incendiary bombs, certain conclusions have been reached.

4. Causes of Damage. High-explosive bombs damaged utility installations by blast, fragmentation, earthshock, debris and, occasionally, by fire. Blast generally damaged aerial wiring, switchboards, transformers, and the like. Although such damage was in most cases comparatively easy to repair, it would, when extended over a large part of the system, cause much disruption of industrial production.

5. Fragmentation. Fragmentation was an effective agent for damage to cables, transformers, switchboards, tanks and similar installations. The effective radius for fragmentation damage was approximately

three times the radius of the bomb crater.

6. Earthshock. Earthshock was effective in damaging underground installations such as gas and water mains, and cables. The maximum radius for earthshock severe enough to do damage was approximately three times the radius of the bomb crater.

7. Debris. Debris in the form of collapsing structural members of industrial buildings did much damage. The degree of this type of damage is closely related to the building type, and it is not possible to predict exactly how much damage may be expected from this source. Generally speaking, however, the utility damage caused by debris roughly amounted to 50 per cent of the structural building damage.

8. Fire. Fire caused by hot fragments from high-explosive bombs did occasionally ignite transformers and switchboards, but, on the whole, not much weight can be given to this damage agent.

9. Incendiaries. Incendiary bombs were indirectly responsible for damage, although it was small compared with high-explosive damage. Electrical installations were often consumed in burning buildings. The amount of damage to be expected from incendiary bombs is therefore closely connected with the degree of combustibility of the buildings concerned.

10. Atomic Bombs. The effect of the atomic bombs on utilities in Hiroshima and Nagasaki was great. The major effect of the atomic bombs on utilities was caused by blast and debris which were effective over a large area. Fire, though effective, was less important. Table 36 summarizes the damage to utilities in Nagasaki and Hiroshima.

B. GENERAL INFORMATION

1. Vulnerability of Utilities. Utilities in Japan, although generally inferior to American systems, adequately served their purposes. Electric and gas plant installations were comparable with American standards, but water and sewer systems were inferior. Underground conduits were rarely used and therefore utility installations were vulnerable to aerial attacks and, in particular, to the effects of the atomic bomb.

2. Condition at End of Hostilities. At the end of the war utilities were in a bad condition because of severe damage caused by aerial attacks. Most industrial utilities were unable to operate adequately, and it would have taken much time to bring them back to their full capacity.

C. DAMAGE ANALYSIS

1. High-explosive Bombs. High-explosive bombs caused damage by blast, earthshock, fragmentation, debris, and fire.

a. Blast. Blast damaged switchboards, transformers and aerial wiring. This damage was generally not serious and could often be repaired within a short time by maintenance crews. Several examples were studied where gas tanks had been collapsed by the blast from 1,000-pound, high-explosive bombs detonating 150 feet away.

b. Earth Shock. Cratering bombs produced shock waves of sufficient magnitude to damage effectively underground installations, such as water and gas mains, within a distance of three to four times the

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TABLE 36

DAMAGE TO PLANT UTILITIES BY THE ATOMIC BOMB

HIROSHIMA - NAGASAKI

SYSTEM	MAX DIST (FT) FROM GZ THAT DAMAGE WAS FOUND			CAUSE OF DAMAGE	OVER-ALL DAMAGE PERCENTAGE			MAN HOURS * ESTIMATED REPAIR TIME	COMPONENTS DAMAGED
	Wood-frame Bldgs	Steel-frame Bldgs	Reinforced-concrete Bldgs	Blast, Fire, Debris	Wood	Steel	RC		
Electric	10,000	5,000	7,000	*	100	40	60	800,000	Transformers, switchboards, cables and overhead electric poles
Gas	7,000	5,000	7,000	*	100	40	40	400,000	Tanks, producers, main and distribution pipe
Water	10,000	5,000	7,000	*	100	30	20	100,000	Water mains and distribution pipes
Communications	10,000	5,000	7,000	*	100	50	60	150,000	Cables and wire
Transportation	10,000	5,000	7,000	*	75	10	10	50,000	Truck and rolling stock

* Japanese estimate

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radius of the bomb crater. Much damage was also sustained by water and gas escaping from ruptured mains. Of the bombs studied in Japan, 500-pound bombs, on a tonnage basis, appeared to be most suitable for damaging underground installations. Damage from earthshock was generally heavy and required a great deal of time and labor to repair.

c. Fragmentation. Fragments damaged the prominent and heavier items of utility equipment, such as switch gear, switch panels, control boxes, telephone switchboards, control centers, pumps, tanks, large overhead steam and gas lines. Elevated water tanks and gas holders were also severely damaged by large fragments; however, these tanks or pipes were easily patched by welding, and did not constitute as serious an item of damage as that of fittings, pieces of rotating machinery, and transformers.

d. Debris. Debris caused severe damage within buildings. This damage depended to a large extent on the degree of structural damage

No break

and upon the nature of the debris. It is estimated that damage by debris to utilities in a building amounted to 50 per cent of the structural building damage. Debris was often severe enough to curtail production in industrial plants even though the machinery was only slightly damaged.

e. Fire. Fire caused by the flame front or from hot fragments was observed, but such cases were rare. Transformers were most vulnerable to this damage agent. The thin-walled casing of the transformer contained a special type of cooling oil which was easily ignited when hot fragments pirced the casing. In such cases the transformers were totally damaged.

2. Incendiary Bombs

a. Incendiary versus High Explosive. Incendiary bombs were widely used on Japanese cities, but their effect on utility installations was less than that of high-explosive bombs.

b. Indirect Effect. In only a few instances was it observed that utility installations had been damaged by fire as a result of direct contact with incendiary bombs. Much fire damage, however, was caused by indirect fires, i.e. fires produced in buildings by the bombs. It is therefore clear that the ability of incendiary bombs to damage utility installations in buildings depended to a large extent on the combustibility of the building.

3. Atomic Bombs

a. Effective Damage Agent. The atomic bombs which detonated above Hiroshima and Nagasaki were extremely effective in damaging utility installations. The limit for this damage was approximately 10,000 feet from Ground Zero (GZ), i.e., the point on the ground vertically below the bomb's point of detonation.

b. Causes of Damage. In contrast to the effects of high-explosive bombs which were in most cases direct, the damage caused by the atomic bombs was mostly indirect (fire and debris), although considerable damage was also caused directly by blast.

c. Degree of Damage. The degree of damage inflicted on utilities was generally not severe, but it was extensive.

(1) Installations Affected. Damage to utility installations is shown in Photos 120 - 143. Switchboards, tanks, cables, steel towers, and electric poles were damaged by blast up to 10,000 feet from GZ. Water, gas and air pipes, cables and switchboxes fixed to steel frames were distorted because of displacement of the collapsing steel structures.

(2) Value of Underground Conduits. Less damage would have been sustained if the utility installations had been carried in underground conduits which is the practice in most United States industrial plants. The damage to underground utilities in both cities was almost negligible.

d. Blast Walls. Reinforced-concrete blast walls, either poured in situ or pre-cast, were used extensively in Nagasaki. They proved to be very effective and saved much equipment from damage by blast and debris.

e. Primary Fire Damage. There was no evidence of primary fire damage to utilities but fires did occur, although infrequently, in steel-frame buildings. The extent of fire damage depended entirely on the buildings' combustibility.

f. Damage to Utilities in Reinforced-Concrete Buildings.

(1) Fire. Damage to utilities in reinforced-concrete buildings was caused largely by secondary fires. The amount of damage in these buildings was severe. However, it must be pointed out that most of the reinforced-concrete buildings had been built originally for school purposes, and therefore had a large amount of interior wooden trimmings. Typical damage in these buildings is shown in Photos 16 to 18.

(2) Debris. Damage to utilities in reinforced-concrete buildings was also caused by debris when part of the structures collapsed. The extent of this damage depended solely on the strength of the structure (Photos 16 to 18).

(3) Effect of Design. If the reinforced-concrete structures had been designed for industrial purposes the amount of damage sustained would have been considerably less.

g. Damage to Utilities in Wood-frame Structures. Utilities in wood-frame structures were most vulnerable to the atomic bombs and sustained total damage in all plants surveyed in Hiroshima and Nagasaki up to 10,000 feet from GZ. (Photo 9).

4. Mean Areas of Effectiveness. MAE's were calculated for both cities as shown in Figure 1. The annular ring method used for computation of MAE's for structures and machinery was also used for utilities. Since Hiroshima had few industries in reinforced-concrete and steel-frame buildings within the damaged area, it was not possible to compute these MAE's. However, in the opinion of the Physical Damage Division, the MAE's and graphs shown in Figure 1 are considered sufficiently accurate for future prediction of utility damage resulting from attacks with atomic bombs. It should, however, be emphasized that the graph for utilities in reinforced-concrete buildings gives too high a value because of the building design described in paragraph 3f (1) above.

5. Recommendations. Utility installations above ground were vulnerable to attacks with atomic bombs; therefore as many as possible of the utility components should be carried in underground conduits; and transformers and switchboards placed above the ground should be protected with reinforced-concrete blast walls.

CHAPTER ~~VII~~ VI

THE ATOMIC BOMBS

A. FOREWORD

1. The advent of the atomic bomb opened up an entirely new field in the study of the destructive power of aerial weapons. Much data relative to the characteristics and effectiveness of conventional high-explosive and incendiary bombs had been collected and evaluated as a result of experiences gained in the European theatre, so that the AAF was able to make remunerative and effective attacks on Japanese targets. But here was an entirely new and revolutionary weapon which possessed the usual characteristics of blast, many times more powerful, and also introduced new elements - heat and radiation. The study of the effects of the atomic bombs on Hiroshima and Nagasaki with respect to physical damage to structures and their contents, utilities, and transportation has been a fascinating one, as well as one fertile in information which will be of inestimable value to planners in many fields of endeavor.

2. One of the purposes of this division was to establish in proper perspective the relationship of the atomic bomb to other weapons by comparisons of relative effectiveness. All in all, the atomic bomb was so much more destructive for its size and weight than any other known bomb that any attempt to minimize it would be not only futile but impossible. It is believed, however, that the colorful and dire predictions of early observers, predictions based on cursory and incomplete study, can be toned down considerably in the light of current, available information. For example, it is interesting to note that the wasted

areas of Hiroshima and Nagasaki did not differ materially, at least in outward appearances, from those of Japanese cities, such as Tokyo, ravaged by incendiary attacks. And in Germany the ruins of such cities as Hamburg and Essen, attacked by both high-explosive and incendiary bombs, differed only in profile because of the type of construction, but the results achieved were the same - total damage; but how these cities got that way as compared with Nagasaki and Hiroshima is still another matter which is discussed in the following pages and in the final report on the European Theatre (PDD Report 68).

3. In many respects, the type of physical damage caused by the atomic bomb was not unusual and was what might well be expected, considering the established physical laws governing the effects of blast pressures. But the degree and extent of this kind of damage were so widespread that many new factors will have to be considered in future calculations. In other respects, the heat generated by the atomic bomb explosion exceeded the limit of ordinary human comprehension. To those of us who are accustomed to thinking only in terms of weather temperatures, the millions of degrees centigrade at the bomb's core represents an astronomical figure; and even the 3,000° to 9,000° centigrade temperature estimated to have hit the atomic areas is fantastic. Its effects, however, definitely establish the stark reality of the situation, leaving no doubt in the observer's mind. Likewise, free neutrons and high-frequency radiations such as gamma rays were something new, at least in warfare. Their effects on the human body and on soil and vegetation are the subject of another Division of the Survey.

4. Study and further experimentation will together point to what is to be done in the future to counteract the effects of the atomic bomb. In the meantime any and all information regarding the bomb's characteristics, behavior, and effects on life, morale, industry, business, utilities, and all aspects of economic endeavor is extremely important to military and civilian planners in their efforts to evaluate the bomb and to provide efficacious counter measures.

5. This report makes no attempt to pass judgment on the over-all effectiveness of the atomic bomb, its purpose being solely to give as complete a summary as possible of the physical damage suffered by the stricken cities as a result of both the direct and indirect effects of the atomic forces. (The complete story of Hiroshima will be found in PDD Report 69, and of Nagasaki in PDD Report 70). Résumés of findings on damage to buildings of all existing types - industrial, commercial, and residential - are included herein, together with certain conclusions concerning the relative degrees of resistance, inherent in the several types, to the direct and indirect results of the atomic bomb. Likewise, building contents vulnerability and degree of damage in relation to types of construction are discussed. Considerable space is devoted to fire since it resulted from both direct and indirect causes and was the source of a large proportion of the physical damage. Other subjects studied and reported on are: damage to machine tools, utilities, bridges, stacks, and services.

B. PRE-ATTACK CONDITIONS

1. Hiroshima

a. The City. Hiroshima, located in the southwestern area of the principal Japanese island of Honshu and at the northwestern corner of the Inland Sea, was an important, modern, administrative, communications, and military center. The seventh largest city in Japan it had had a wartime peak population of 380,000, but, as the result of several evacuations, that figure had been reduced to an estimated 245,000 by 6 August 1945, the date of the atomic-bomb attack. The city had developed on the delta of the Ota River and spread over seven finger-like islands formed by six river channels. Except for four small, rocky formations, only one of which was as much as 220 feet high, the delta was uniformly flat and about 10 feet above sea level. The evenly exposed area stretched 6,500 feet in all directions from the heart of the city, so that within the city boundaries there were approximately 26.5 square miles.

b. Built-upness. Densely built-up areas (over 40 per cent of plan area) or moderately built-up areas (20 to 40 per cent of plan area) extended for 23,000 feet on the north-south axis and 17,000 feet on the east-west. Around the central core of the city in a concentric area with a minimum radius of 6,000 feet occurred the greatest density of dwellings and wood-frame structures. In addition, there were located in this area many wall-bearing brick buildings and fewer steel-frame structures which were representative of the post-1923, earthquake-resistant design. Interspersed among these buildings were the low, flimsily-built shops, dwellings, and offices of typical Japanese wood design and construction.

c. Use. The central area of 6,000-foot radius comprised the principal commercial section of the city, together with large parts of the residential and military sections, but there were no industries of appreciable size nearer than 8,900 feet to the city center, the main industries being located mostly on the eastern perimeter of the city or on the southern tips of the islands. Seventy-five per cent of the 245,000 inhabitants at the time of the attack were in the congested 4-square-mile city center, which gave a population density of 46,000 persons per square mile.

d. Vulnerability. It can readily be seen from the foregoing, that Hiroshima had no natural barriers to protect it from the widespread effects of the atomic bomb, and that fact coupled with population density, flimsy construction, and building congestion, made it a choice target for maximum results.

e. Pre-Attack Sequence. The air-raid "alert" (first audible public warning) was sounded at 0720 on 6 August 1945. It was the general policy in Japan at the time not to give the air-raid "alarm" unless planes appeared in force, and, as only three aircraft were seen in the sky, the "all clear" (release-from-alert) was sounded at approximately 0740, whereupon the people resumed their customary daily tasks and practically no one was in shelters. Because of the time of day, many residences had fires for the purpose of cooking measl; most of the industrial workers were already at the factories; and many professional men and commercial employees were on the way to their offices or businesses, so that traffic was comparatively heavy. Thus the scene was set with all conditions favorable for maximum casualties and damage when the bomb exploded in the air shortly after 0800.

2. Nagasaki

a. The City. Nagasaki was located on the western coast of Kyushu island. It lay on a narrow coastal strip encircling a long, narrow bay and extended up two river valleys, one to the north (Urakami), the other to the northeast (Nakashima), the two being separated by a mountain spur. An important industrial city, its greatest population during the war had been 288,000 but it had dropped to 230,000 on 9 August 1945, the date of the atomic-bomb attack.

b. Built-upness. The main residential and commercial districts were intermingled in the two river valleys. The metropolitan area of the city comprised about 35 square miles, of which only 3.8 square miles constituted the heavily built-up portion. Seventy per cent of the latter was 30 per cent or more built up. Population density in the 3.8-square-mile area was in the neighborhood of ~~79,000~~ 60,500 per square mile.

c. Use. Unlike the situation in Hiroshima where the large industries were on the fringe of the city, the industrial zone of Nagasaki was located in the Urakami River valley which averaged three-quarters of a mile in width; the Nakashima valley contained the main commercial and residential areas.

d. Vulnerability. Compared with Hiroshima, the topographical features of Nagasaki with its intervening hills ~~offered~~ afforded protection from widespread blast effects of the atomic bomb, and also served to prevent fire spread. This statement is confirmed by the fact that, although the bomb which exploded over Nagasaki was reported to have been more powerful and was detonated closer to the ground, the damage was less widespread but of greater intensity within the area affected. On the other hand, the density of population, the typical flimsy construction, building congestion and concentration of industry in one valley were all factors favorable to effective atomic-bomb damage.

e. Pre-Attack Sequence. The USAAF had been sending reconnaissance planes in small numbers over the Nagasaki area daily for several weeks prior to 9 August. The "alert" would be sounded and, pursuant to local variations of shelter procedure, the aged, sick, women, children and others not engaged in essential activities would go to shelters. There they would wait expectantly, but nothing would happen. This was repeated day after day, not once but several times. On the day immediately preceding the atomic-bomb attack, people had been in the shelters for two hours to no purpose, and had then been released. A spirit of carelessness developed and it proved to be their undoing. On the ninth of August, a small flight (2 planes) to which the people had become accustomed appeared over the city - just other reconnaissance ships. The "alert" was sounded. Why bother going to shelter? Nothing would happen. The "alarm" howled on the sirens, to be followed in a short time by the "release-from-alarm" which merely confirmed the belief of the population that there was no danger. And then at 1102 came the catastrophic detonation.

C. THE ATTACKS

1. The first atomic bombs to be used for military purposes were dropped on the ill-fated cities of Hiroshima and Nagasaki and inaugurated not only a totally new concept of aerial warfare, but provided a basis for the analysis of bomb damage and effects on a plane which had not been heretofore considered. For the first time, instead of studying the damaging effects of a number of missiles on individual structures, consideration had to be given to entire blocks of buildings wholly or partly demolished, some appearing to have been flattened as though by a giant hand, to widespread areas of destruction and desolation measured in square miles rather than in square feet or acres; and to large, fire-swept urban areas, all resulting from the air burst of one bomb.

2. The first atomic bomb was dropped on Hiroshima at 0816 hours 6 August 1945; the second on Nagasaki at 1102 hours 9 August 1945. The two attacks were made under somewhat similar circumstances, both as to weather which was clear over the two targets with winds of low velocities, and as to conditions on the ground. Both cities had been subjected to previous high-explosive attacks which had caused relatively little damage; residents had become accustomed to the presence of reconnaissance planes over their cities; no large groups of planes had been reported to indicate that any large-scale attacks were imminent; air-raid alarms had been sounded, then cancelled; few persons were in shelters; defense and protective forces were not fully manned; and in

neither instance were either the citizens or responsible military and government officials in any way prepared for the sudden, violent, catastrophic onslaught from the skies.

3. Both bombs detonated at certain heights in the air. The explosions were characterized by a blinding flash, followed by an intense heat wave, and crushing blast pressures. Scientists estimated that the detonation of the atomic bomb, lasting only a millionth of a second, created a ball of fire hotter than the center of the sun (70,000,000°C), and released radiations ranging from beyond the infra-red, through the visible spectrum, and into the ultra-violet and gamma rays. The Nagasaki bomb was reported to be an improved and more powerful version of the weapon used in the Hiroshima attack, and was detonated at a slightly lower altitude.

D. EFFECTS

1. The results of the atomic-bomb explosions which immediately paralyzed the facilities and normal life of two cities were various and, in many instances, as spectacular as the bomb itself. Outstanding among these were the extreme distances at which blast damage occurred; the wide area of total damage; the ignition and scorching of combustible materials and the searing of noncombustibles at great distances.

a. Buildings. In Hiroshima approximately 60,000 of an estimated total of 90,000 buildings over an area of 9.5 square miles were totally or heavily damaged. Dwellings and structures of Nagasaki were demolished throughout an area of 1.8 square miles, or within a radius of 5/8 mile from Ground Zero, and other structures suffered varying degrees of damage within a $2\frac{1}{2}$-mile radius. Superficial and minor damage was experienced up to 8 miles at Hiroshima, and only as far as 10 miles at Nagasaki.

b. Machine Tools. Machine tools in Hiroshima were totally or heavily damaged throughout an area exceeding four square miles. In Nagasaki various degrees of damage to machine tools extended up to 6,500 feet from Ground Zero. The degree of damage and the number of machine tools affected depended largely on the types of structures in which they were housed. Damage resulted from blast effects, debris, fire, and exposure to the elements.

c. Bridges. The timber bridges in both cities were the most heavily damaged by blast and fire. Those of steel and concrete were affected to a lesser degree, and heavy concrete bridges were the least affected of any. Some steel bridges were collapsed, and others were structurally damaged. At Hiroshima, in many cases, bridges which were not seriously damaged could not be utilized because of masses of debris from adjacent buildings which clogged the approaches.

d. Stacks. Reinforced-concrete stacks were found to be generally resistant to blast effects, only four of approximately 30 within 6,000 feet of Ground Zero having been damaged in Nagasaki. All steel and brick stacks within the same area were totally damaged. In Hiroshima, 45 per cent of all stacks within a radius of 1.6 miles were damaged beyond use.

e. Public Utilities. All public utilities were damaged and completely disrupted. Both cities were temporarily without transportation, electricity, communications, gas, water, and sewers. Within a period of several days, however, some of these services, such as railroad and street railway transportation, electric power, and water supply, were available to a limited degree in certain areas, mostly for essential use.

f. **Fire**. Fires, caused by radiant heat from the detonation of the bomb, as well as by electrical short circuits and as a result of inflammable debris falling on or upsetting open-flame devices, accounted for large areas of damage in both cities. An area of 4.4 square miles was burned over in Hiroshima, and in Nagasaki approximately one-third of the densely built-up area (3.8 square miles) was swept by flames. Fire defenses in both cities were considerably limited as the initial bomb blast had seriously crippled the fire-fighting organizations, damaged equipment and killed or injured personnel.

E. DAMAGE TO BUILDINGS

1. Building Types. Buildings in both Hiroshima and Nagasaki ranged from modern, reinforced-concrete structures and steel-frame industrial buildings to wood-frame buildings and the typical Japanese dwellings which were entirely of wood construction except for tile roof covering. Some of the commercial buildings were of reinforced concrete of excellent material and earthquake-resistant design. Those of multi-story construction and aseismic design were usually heavier and stronger than similar types in the United States. Quality of concrete and workmanship varied considerably, however, and some buildings of substandard design and construction were found. There were other buildings

of load-bearing brick-wall construction, and some which had reinforced-concrete frames. The industrial-type buildings were generally of steel-frame construction, single-story, having either saw-tooth or monitor-top roofs. These buildings were usually covered with corrugated-asbestos or corrugated-metal roofing and siding. Despite the encouragement of Western construction practices and the adoption by the Japanese government of aseismic design for large buildings, the shortage of critical building materials and the lack of enforcement of the building code resulted in the predominance of wood-frame and wood-pole construction over all other types in every city. The wood-frame buildings, for the most part, comprised dwellings, combination shop-dwellings, and small commercial and industrial buildings. Typical wood buildings in Japan had light frames, relatively heavy roofs supported by slender columns, and poorly designed joints. Buildings of this type were, of course, highly vulnerable to fire and blast.

2. <u>Extent of Damage</u>

a. <u>Structural Damage</u>. Widespread structural damage was found in Hiroshima up to between 6,000 and 7,000 feet from Ground Zero and up to a maximum of 11,000 feet in Nagasaki. The area of damage in Nagasaki, however, was not uniform as it was in Hiroshima. The bomb in the latter city detonated over its center where the land was level; at Nagasaki, it detonated over a valley away from the center of the city and the blast travelled along the valley in both directions. The degree of damage at Nagasaki was greater than at Hiroshima, although the actual area in which damage occurred was smaller. At Nagasaki 30.7

per cent or 1.8 square miles of the built-up area of the city suffered structural damage; in Hiroshima, 69 per cent of the city's buildings over an area of 9.5 square miles were totally or heavily damaged. Figures 32A and 32B, both drawn to the same scale, show the relative areas of structural damage in the two cities, caused by fire and blast and those caused by blast alone. In comparing the extent of damage among the several types of buildings in the two cities, it must be considered that there was a marked difference between the areas affected by each bomb. In Hiroshima, for example, the area under the point of detonation comprised a domestic and commercial zone where there were many houses but few industrial buildings; the bomb at Nagasaki was dropped over a zone that was both domestic and industrial, but with numerous industrial buildings and fewer dwellings than the bomb-affected area of Hiroshima. In fact, the bombed area of Nagasaki contained the most strongly built structures in the city. Although the degree of damage in both cities decreased as the distance from Ground Zero increased, the rate of decrease was not uniform in similar types of buildings. This lack of uniformity resulted largely from the differences in design and quality of workmanship in similar types of buildings. Further, it was often impossible to obtain a reliable estimate of the damage which might have been expected at various distances from the point of detonation when there was an insufficient number of buildings of the same general types exposed to the effects of the bomb at similar distances from Ground Zero.

(1) Reinforced-Concrete Buildings. The strongly built, heavy, multi-story, reinforced-concrete and concrete-

frame buildings were by far the most resistive to the blast effects of the atomic bomb. These buildings

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NAGASAKI, JAPAN

U. S. Strategic Bombing Survey
PHYSICAL DAMAGE DIVISION
Figure 32A

HIROSHIMA, JAPAN

U. S. Strategic Bombing Survey
PHYSICAL DAMAGE DIVISION
Figure 32B

were heavily damaged only in an area relatively near the point of bomb detonation. A much higher percentage of buildings of similar construction but of lighter materials and inferior design was totally or heavily damaged at greater distances. At Nagasaki, 9.5 per cent of the floor area of reinforced-concrete buildings in the area between 2,000 and 3,000 feet from Ground Zero, the majority of which were of excellent material and earthquake-resistive design, was totally or structurally damaged. In the area between 4,000 and 5,000 feet from Ground Zero, however, 56 per cent of the buildings of this type, but of lighter construction, suffered total or heavy damage. Differences between the physical characteristics of the terrain and types of construction in the two cities, and possibly differences between the forces created by the two detonations accounted for variations in extent of structural damage to this type of building. Equivalent blast effects were found in Nagasaki over greater areas. Structural damage to reinforced-concrete buildings in that city occurred within an area of 0.43 square mile, compared with an area of 0.05 square mile of similar heavy damage in Hiroshima. It is believed that more widespread damage to this type of building would have resulted from detonation of the atomic bomb at a lower altitude without seriously affecting the extent of damage to other classes of buildings.

(2) Steel-Frame Buildings. Single-story, light, steel-frame industrial buildings were heavily damaged throughout areas of approximately equal size in both cities. Damage to structures of this type covered an area of 3.4 miles at Hiroshima; 3.3 miles at Nagasaki. There were no heavy, steel-frame buildings in Hiroshima, and damage to this class of structures could be studied only at Nagasaki where structural damage extended over an area of 1.8 square miles. Steel-frame buildings covered with corrugated-asbestos siding and roofing generally suffered less structural damage than those buildings having corrugated-iron or sheet-metal covering. The blast effects immediately ripped off or crumbled the asbestos material, leaving no wide surfaces exposed, against which damaging blast pressure could be exerted and transmitted to the framework. Metal siding, however, transferred pressure to the structural members, causing distortion or general collapse.

(3) Load-Bearing Brick-Wall Buildings. Buildings of load-bearing brick-wall construction were extremely vulnerable to blast and therefore suffered heavily from

the effects of the atomic bomb. Multi-story brick buildings, which were studied only at Hiroshima, were structurally damaged within an area of 3.6 square miles. Single-story brick buildings were damaged in the same city within an area of 6 square miles, and within an area of 8.1 square miles in Nagasaki. In Hiroshima, collapse or serious cracking of walls occurred in buildings having 24- to 27-inch walls up to 3,700 feet; and in buildings having 9-inch walls, similar damage was inflicted up to 8,200 feet from Ground Zero. In Nagasaki 100 per cent of the floor area of the brick buildings up to 3,000 feet from Ground Zero suffered total or heavy structural damage. Between 3,000 and 7,000 feet, over 75 per cent of the floor area of those studied was similarly damaged, and various degrees of structural damage extended as far as 11,000 feet from Ground Zero. Many of the brick buildings which were heavily damaged at great distances from Ground Zero were set somewhat apart from other structures and consequently had little shielding from blast.

(4) Wood-Frame Buildings. Wood-frame industrial and commercial buildings in Hiroshima were structurally damaged up to 7,300 feet from Ground Zero, and within an area of 8.5 square miles. In Nagasaki, buildings

buildings of similar construction were structurally damaged within a radius of 10,000 feet from Ground Zero, or within an area of 9.9 square miles. These buildings were generally of inferior construction and design. Supporting members and columns were easily buckled by blast pressure on roofs, leading to mass distortion and collapse of framework. Structural damage to wood-frame buildings as a result of blast generally extended well beyond the area of fire damage. Wood-frame and all-wood domestic buildings in Hiroshima were totally or heavily damaged throughout an area of 6 square miles; in Nagasaki, throughout an area of 7.5 square miles.

(5) Mean Areas of Effectiveness (MAE's). No great significance can be attached to the areas of structural damage to any one type of building without considering the total area of the buildings of that type exposed to the blast. A better estimate of the bomb's effectiveness against structures of certain types can be obtained by computing the mean areas of effectiveness (MAE's) and making comparisons at the two cities on that basis. To obtain a sufficient number of buildings with structural damage for comparison in the two cities, it was necessary to group various buildings of the same or similar type of construction. These

groups lack the greater refinement of classification which is found in the data for high-explosive bombs. The categories of buildings compared at Hiroshima and Nagasaki, however, were essentially the same and reacted similarly to blast. The mean areas of effectiveness of the atomic bomb for structural damage around Ground Zero and the radii of the MAE's for the different classes of buildings in both cities are shown in Table 1. To find the MAE's for the various building categories the annular-ring method was used, except for wood dwellings in Group 8. The MAE's for the latter group were computed by the average-circle method. The MAE's comprehend structural damage caused by blast alone, fire and blast combined, and fire alone. The following paragraph of this section (Paragraph 3) indicates the percentages of damage resulting from those causes. In comparing MAE's at Hiroshima with those at Nagasaki, it should be understood that the figures are for two bombs whose heights of detonation differed by some 15 per cent, and that the Nagasaki bomb was reported to have been an improved and more powerful version of the atomic bomb dropped over Hiroshima. A comparison of the building groups for which there were data for both cities indicated the more powerful Nagasaki bomb produced larger mean areas of effectiveness. The MAE for Group 2 of Hiroshima is about 10 per cent of that for Nagasaki. Some of the buildings in Group 2 at Nagasaki, however, were more vulnerable to blast because of their position on or near the ridge of the valley. Group 4 has about the same value for both cities, perhaps explained by the relatively greater extent of shielding by other buildings at Nagasaki. The MAE's at Hiroshima for Groups 6 and 7 are about 75 per cent and 85 per cent, respectively, of those for Nagasaki. In Group 8, the MAE for Hiroshima is 80 per cent of that for Nagasaki. The MAE's at Hiroshima and Nagasaki for Group 7 are larger than those for Group 8 because the buildings in the latter group were better constructed and probably more shielded from the blast. The extent of structural damage by blast to the different types of buildings, as well as the MAE for each type, is shown graphically in Figures one through five. For almost every category of building the fraction of damage was greater for Nagasaki than for Hiroshima at corresponding distances from Ground Zero.

b. <u>Superficial Damage</u>. Superficial damage, consisting of the stripping of wall and roof covering, and the removal of light partitions, windown glass and frames, extended to as far as 8 miles from Ground Zero

TABLE 1

MEAN AREAS OF EFFECTIVENESS (MAE'S) FOR HIROSHIMA AND NAGASAKI

Building Group	Description of Building Type	Total Floor Area to Limit of Structural Damage (1000's of sq ft)	Total Floor Area of Structural Damage (1000's of sq ft)	Mean Area of Effectiveness (square miles)	Radius of Mean Area of Effectiveness (feet)
(1) Hiroshima	Multi-story, earthquake-resistant buildings only	597	34	0.03	500
Nagasaki		----	---	----	----
(2) Hiroshima	Multi-story, steel- and reinforced-concrete-frame (Including earthquake-and-non-earthquake-resistant buildings)	637	54	0.05	700
Nagasaki		694	121	0.43	2000
(3) Hiroshima	One-story, heavy, steel-frame	----	----	----	----
Nagasaki		1138	436	1.8	4000
(4) Hiroshima	One-story, light, steel-frame	94	51	3.4	5500
Nagasaki		741	484	3.3	5400
(5) Hiroshima	Multi-story, load-bearing brick-wall	189	158	3.6	5700
Nagasaki		----	----	----	----
(6) Hiroshima	One-story, load-bearing brick-wall	283	169	6.0	7300
Nagasaki		390	246	8.1	8500
(7) Hiroshima	Wood-frame, industrial-commercial	523	154	8.5	8700
Nagasaki		1475	1126	9.9	9400
(8) Hiroshima	Wood-frame domestic	----	----	6.0	7300
Nagasaki		----	----	7.5	8200

in Hiroshima and up to 4 miles at Nagasaki. In addition to the 30.7 per cent of the built-up area of Nagasaki which suffered structural damage there was an additional 9.3 per cent which was superficially damaged, roof stripping and disturbance of roof tile having been found as far as 19,000 feet from Ground Zero. Wall and roof stripping was found at Hiroshima up to 22,000 feet, and glass breakage was reported beyond 37,000 feet. There were instances in which corrugated-asbestos siding and roofs were stripped from steel-frame buildings without damage to the structural framework. There were other buildings where evidence indicated that the initial damage by blast was superficial, but subsequent fire had resulted in structural damage through warping and softening of steel supporting members. Cases of this nature, however, were relatively uncommon. Superficial damage, although not so important nor so spectacular as building collapse and heavy structural damage, extended the effectiveness of the bomb by exposing machinery, tools, and supplies to the elements, and by making more difficult the work of clearance and the restoration of necessary shelter for victims of the attacks.

3. Causes of Damage. The structural damage to buildings in both cities was due to blast alone, blast and fire combined, and fire alone. Since the limits of structural blast damage to buildings extended beyond the burned-over areas, except for multi-story, steel- and reinforced-concrete-frame buildings, it is believed that in most cases buildings which suffered mixed damage were structurally damaged by the initial blast, and subsequent fires merely intensified the damage. Superficial

damage, for the most part, resulted from blast. There were wooden, tile, and some metal surfaces which were charred, scorched, or otherwise marked by flash burns, which might be classed as superficial damage, and a number of buildings affected by fires which caused superficial or interior damage but which were extinguished before structural or widespread damage resulted. At Nagasaki, the damage was due mostly to blast and blast plus fire. At Hiroshima, the structural damage to buildings studied was mainly due to blast. It was often possible in the latter city, on close inspection, to separate blast-damage areas from fire-damage areas. There was no evidence found of earth-shock damage to building.

a. Blast. The largest percentage of structural damage attributed to blast alone was almost 85 per cent, and occurred in the heavy and light, steel-frame buildings.

b. Blast and Fire. About 75 per cent of the structural damage in the reinforced-concrete and the load-bearing brick-wall buildings was due to blast plus fire. For single-story, light, steel-frame buildings, 20 per cent of the structural damage was due to blast plus fire.

c. Fire. Only in load-bearing brick-wall buildings and industrial and domestic wood-frame buildings was there structural damage caused by fire alone, and this was less than 10 per cent of the total structural damage for these building categories. Twenty-five per cent of the structural damage to multi-story, earthquake-resistant buildings was due to fire alone. For multi-story, steel- and reinforced-concrete frame buildings, both earthquake- and nonearthquake-resistant, 15 per cent of all structural damage was due to fire alone. Less than five per cent of the structural damage to multi-story, load-bearing brick-wall class was attributed to fire alone.

4. Characteristics of Damage

a. Blast. The atomic-bomb detonations were characterized by far-reaching, crushing blast effects, ~~The blast effects produced~~ which were uniform and essentially those of a conventional high-explosive weapon, although on a much larger scale. Instead of producing localized effects, entire buildings were crushed or distorted as units over a wide area. The effect of the atomic bomb on buildings was usually that of a powerful push which shoved them over or left them leaning. Buildings near Ground Zero, where the blast pressure was almost vertically downward, were crushed or, in some instances, had their roofs blown in with relatively little damage to walls. At greater distances, they were exposed to both vertical and horizontal forces, thereby suffering damage both to roofs and walls facing the blast. At considerable distances, the pressure was principally in a horizontal direction and the major portion of the damage occurred to walls facing the blast. Blast damage in Hiroshima spread almost uniformly in all directions from Ground Zero, resulting in an approximately circular area of devastation. The area of damage at Nagasaki was not so regular nor so evenly spread. Because of the topographical formation at this city, the force of the blast was confined principally to the valley, resulting in a comparatively long, narrow, irregular area of destruction, the fringe of which was at greatly varying distances from Ground Zero. The blast effects were most striking at Nagasaki, where the sides of concrete buildings facing the detonation were stove in as if wooden boxes. The skeletons of lone lines of steel-frame factory sheds, over a mile from Ground Zero, leaned away from the explosion. Strongly-built steel members were bent and twisted, and roofs of reinforced-concrete buildings were crumpled and collapsed. At Hiroshima, although similarly characteristic damage was experienced, the more strongly-built reinforced-concrete structures of that city were damaged only relatively near the point of detonation, and beyond that area their burned-out, but otherwise undamaged, structural frames stood amidst the twisted steel and rubble which marked the locations of former brick and steel-frame buildings.

(1) Negative Phase. The negative phase of the atomic-bomb detonation, at which time below-atmospheric pressures existed, occurred during the period immediately following the passing of the initial, positive blast wave and resulted in characteristic damage such as glass and window shutters, and occasionally plaster wall covering, being blown out toward the blast. Damage of this nature, however, was relatively uncommon and all significant damage to buildings occurred during the positive phase when the pressure was greater than atmospheric.

(2) Shielding. Some buildings were shielded from the direct effects of the bomb blast by others, and

therefore suffered less damage than comparable structures at the same distance from Ground Zero. At points near Ground Zero there was little or no shielding because of the height of the buildings, which was limited to 100 feet by the Japanese building code, and the height of detonation of the bombs. Shielding played a more important role in Nagasaki where hills divided the city, and, as a result, more than one-half the residential units escaped serious damage.

(3) Reflection and Diffraction. Reflection and diffraction effects were observed in both Hiroshima and Nagasaki. Diffraction was evidenced by damage in locations where shielding should have afforded some degree of protection had the blast wave travelled in a straight line. It is considered that this phenomenon was responsible for a considerably increased proportion of damage in both cities. There was evidence of reflection of blast in the damage to parapet walls on the side away from the bomb while parapet walls facing the detonation remained undamaged. In these cases it appeared likely that the blast wave reflected from the roof surface reinforced the blast impinging directly upon the wall.

b. Fire. Widespread fire damage may also be described as a characteristic result of the atomic bomb explosions. Fires were ignited by the radiant heat of the atomic-bomb detonation within a radius of 3,000 feet from Ground Zero at Nagasaki, and up to 4,000 feet at Hiroshima. The majority of these fires started in dwellings and other buildings of combustible construction or containing combustible material, and in the debris created by the blast. Other fires which reached major proportions were started over wide areas in both cities by secondary causes, or as an indirect result of bombs blast, such as debris knocking over or falling on open-flame devices and ignition of combustible building material or debris by electrical short circuits. Fire damage effects were more intense and greater in proportion to other types of damage in Hiroshima than in Nagasaki. The causes and extent of fire damage are discussed in detail in another section of this chapter.

F. DAMAGE TO MACHINE TOOLS

1. Extent of Damage. The major industrial plants in Hiroshima were located about one and a half miles from the center of the city, and the machine tools in them were not damaged. Numerous small engineering shops, however, were located within the area affected by the bomb and virtually all machine tools in these buildings within 3,500 feet of Ground Zero were heavily damaged. These shops represented only one-quarter of the city's total industrial production. At Nagasaki no damage to machines and equipment was recorded outside a radius of 6,500 feet from Ground Zero. Damage up to 6,000 feet varied between 5 and 10 per cent of the total, except in wood-frame buildings where the damage was 95 per cent. A total of 26 per cent of all machine tools in the industrial plants affected by the atomic bomb was damaged. Damage to

auxiliary equipment and plant utilities amounted to 45 per cent, as these installations were of lighter construction and presented larger surface areas to the blast. Damage to machine and building contents, as in the case of other types of weapons, was less than damage to the buildings. The extent and kind of damage to machinery depended almost entirely on the construction of, and the degree of damage sustained by, the buildings in which they were contained.

a. Reinforced-Concrete Buildings. No reinforced-concrete buildings in Nagasaki were structurally damaged or had their contents damaged beyond 4,700 feet from Ground Zero. Within that distance, however, 86 per cent of the machine tools sustained damage. Damage to small tools amounted to 45 per cent. Raw materials and semi-finished products sustained 10 per cent damage. There were no reinforced-concrete shop buildings in Hiroshima.

b. Steel-Frame Buildings. The maximum range for damage to industrial steel-frame structures in Nagasaki was 5,600 feet. In those buildings 21 per cent of the machines and 36 per cent of the equipment sustained damage of varying degrees. Small tools sustained damage amounting to 65 per cent. A relatively small number of tools was damaged in buildings of similar construction in Hiroshima, although 42 per cent of the total floor area was structurally damaged. This may be explained by the fact that the blast caused mass distortion of the steel frame without tearing loose heavy structural members, and wall and roof sheathing debris was light. The major portion of machine damage occurred in buildings which burned.

c. Brick Buildings. At Hiroshima, 28 per cent of the machine tools housed in load-bearing brick-wall buildings were damaged. All machine tools in one building which was burned out were heavily damaged. There were no machine tools in this type of building in Nagasaki.

d. Wood-frame Buildings. Only 3 per cent of the machine tools in wood-frame buildings damaged by blast were heavily damaged at Hiroshima. All machine tools in buildings which burned were seriously damaged. At Nagasaki, 95 per cent of the machine tools in this type of structure suffered damage. These buildings, however, were utilized only as temporary auxiliary machine shops for industrial plants and their importance from an industrial standpoint was relatively small.

2. Causes of Damage. The principal causes of damage to machine tools and building contents were fire, debris, and weather exposure. Because of the differences between Hiroshima and Nagasaki in the housing of machines, the locations of their industrial plants in relation to the points of detonation, and the fact that a larger area of Hiroshima was affected by fire, the causes of damage to machine tools and equipment varied considerably in the two cities in buildings of comparable types.

a. Reinforced-Concrete Buildings. ~~There were~~ Machine tools were housed in buildings of this type in Nagasaki only. Debris, in the form of collapsed parts of the buildings, was the major instrument of damage in this type of structure and accounted for 80 per cent of the total damage to machine tools; fire accounted for 9 per cent; and weathering effects, 11 per cent.

b. Steel-Frame Buildings. Blast, debris, and lateral movement of structures caused 70 per cent of the machine-tool damage at Nagasaki; 27 per cent of the damage was ascribed to weathering effects; and fire accounted for only three per cent. At Hiroshima, moderate initial damage to machine tools in buildings of this type resulted from blast, but in the burned-over section of the city, there was almost total damage to machinery by fire. In buildings outside the fire area there was some exposure damage.

c. Brick-Wall Buildings. Machine tools were found in this type of structure only in Hiroshima. Debris caused serious damage to only 5 per cent of the machine tools in these buildings although 30 per cent of the total floor area was structurally damaged. In those buildings which burned because of the combustibility of building material and contents, 23 per cent of the machine tools were seriously damaged by fire.

d. Wood-Frame Buildings. At Nagasaki 54 per cent of the machine-tool damage in wood-frame buildings was due to exposure to the elements. Fire damage accounted for only 10 per cent of the damage, and debris and mass movement of the structures accounted for 26 per cent. The most serious damage to heavy machines was the overturning and fracturing of machine castings. Blast and a combination of blast, fire, and debris accounted for 10 per cent of the machines. In Hiroshima, debris caused total or heavy damage to only 3 per cent of the machine tools in these buildings, although 64 per cent of the total floor area was structurally damaged by blast. Serious damage resulting from debris was caused only by falling overhead shafts and pulleys. Mass movement of buildings caused some damage, but the major portion of damage was due to fire which burned buildings and their contents.

G. DAMAGE TO BRIDGES

1. Types and Construction of Bridges

a. Hiroshima. There were 81 important bridges scattered over the entire city of Hiroshima, ranging from 260 to 15,600 feet from Ground Zero. These served not only for local transportation needs but also as overcrossings for the city's services and utilities. Of those studied, the 39 highway bridges, comprising 14 timber, 15 concrete, and 10 of steel construction were most numerous as a class. There were nine street railway bridges, most of which were in the heart of the city, consisting of two timber, one reinforced-concrete, and six steel bridges. The six railroad bridges, of strongly-built, steel construction, were, as a class, most distant from Ground Zero. There were four pedestrian bridges of timber, and seven bridges (4 timber and 3 steel) which served as aqueducts and over-crossings for utilities. The bridges in general were designed to carry lower loadings than comparable structures in the United States. The design, construction, and materials appeared to be inferior to United States standards, except for the steel-plate-girder bridges and steel-truss aqueducts.

b. Nagasaki. The 35 bridges studied at Nagasaki, all within 7,650 feet of Ground Zero, were used to span either the main body of the Urakami River or its tributaries. They were of relatively short span as nowhere did the width of the river exceed 240 feet. The maximum length of a single span was 120 feet. There were 16 reinforced-concrete bridges of the T-beam type; three curved-chord, steel-truss bridges; two of stone-arch construction; one reinforced-concrete arch; six plate-girder bridges; two timber bridges; one of wood-and-concrete construction; one of wood-and-steel construction; and three bridges of reinforced concrete and structural steel. These bridges covered a wide variety of types but none was outstanding or original in design.

2. Extent and Causes of Damage. Of the 35 bridges in Nagasaki, at distances varying from 300 to 7,650 feet from Ground Zero, four were totally or heavily damaged by blast or fire and six others sustained some degree of structural damage. At Hiroshima, 17 bridges were totally or heavily damaged, and 10 others suffered degrees of damage ranging from displaced and distorted decks and minor structural members to broken railings, curbs, posts, and copings. In terms of deck area, 33 per cent of the 19 timber bridges and four per cent of the 23 steel bridges were totally damaged by blast and fire. None of the 15 concrete bridges suffered total damage. Proximity to Ground Zero did not seem to affect seriously the heavily-built concrete bridges, possibly because of the mass of the bridges and the vertical action of the blast in the direction of their greatest strength, the design of bridges being such as to resist heavy vertical loads. Bridges of less mass but farther from Ground Zero were damaged by displacement which resulted in distortion and failure of members. Plate-girder bridges do not possess large mass, and offered relatively greater surfaces to the blast. Wood bridges were particularly vulnerable to the atomic bomb, sustaining total damage by

fire and blast in Nagasaki up to 5,760 feet from Ground Zero, and in Hiroshima, up to 4,670 feet from Ground Zero. Steel railroad bridges in Hiroshima, being most distant from Ground Zero (5,580 to 8,480 feet), completely escaped damage except for radiant heat effects which to a minor degree on five bridges discolored the paint on girders facing Air Zero.

a. Blast. At Nagasaki two steel-plate-girder railroad bridges, one 840 and the other 900 feet from Ground Zero, were displaced and suffered heavy structural damage as a result of blast. One timber bridge was totally demolished by blast, 5,760 feet from Ground Zero. Two bridges, one of steel and concrete, the other concrete, 1,950 and 2,330 feet from Ground Zero, respectively, had spans blown off. In addition, the decks of the remaining spans of the steel-and-concrete bridge were blown 150 feet away. Four concrete bridges from 300 to 1,710 feet from Ground Zero sustained lateral displacement from one to eight inches as a result of blast. Blast damage to six other concrete bridges at Nagasaki at distances from 750 to 3,750 feet from Ground Zero ranged from displacement of deck and spalling of concrete girders to demolished railings. At Hiroshima, two steel, street railway bridges 1,000 and 4,670 feet, respectively, from Ground Zero were heavily damaged by blast. One steel highway bridge, 1,190 feet from Ground Zero, was totally collapsed. Five concrete (4,270 to 6,450 feet from GZ) and five steel highway bridges (260 to 7,600 feet from GZ) were damaged in extent ranging from distorted decks to superficial damage, such as blown-off railings and trim. Flood and typhoon were credited with damaging 9 timber, 7 concrete, and 3 steel bridges at Hiroshima between 17 September and 5 October 1945. It is considered probable that blast loadings from the atomic bomb had weakened some of these bridges and left them in a vulnerable condition.

b. Fire. At Hiroshima five timber highway bridges were structurally damaged by fire. One timber pedestrian bridge 4,760 feet from Ground Zero was completely consumed by fires which spread from adjacent areas. No bridges at Nagasaki were structurally damaged by fire alone but superficial damage in the form of burned ties was sustained by a steel railroad bridge 1,650 feet from Ground Zero at Nagasaki.

c. Blast and Fire. One timber bridge in Nagasaki, 5,460 feet from Ground Zero, was completely demolished by blast and fire. At Hiroshima, one timber street railway bridge 4,670 feet from Ground Zero was totally damaged. In addition one steel and four timber bridges, used as aqueducts and over-crossings at Hiroshima, totally collapsed as a result of blast and fire, and two other steel bridges were structurally damaged. These seven bridges carried water mains, telephone wires, and low- and high-pressure gas mains.

H. DAMAGE TO STACKS

1. Types of Stacks. Stacks in both Hiroshima and Nagasaki were for the most part of reinforced-concrete, brick, or steel construction. Reinforced-concrete stacks were the most numerous; those of brick construction were second; and steel stacks were in the minority. The average height of all stacks was less than 70 feet. There were few over 100 feet, the highest in Hiroshima being 120 feet. Several other

types were in use, such as vitrified-tile and asbestos-pipe, but these were not considered worthy of study.

a. Reinforced-Concrete Stacks. Concrete stacks were generally well designed and were sufficiently strong to withstand heavy wind loads, as well as the effects of earth tremors. Mediocre quality of workmanship, however, was reflected in the lack of care in placing reinforcing steel and in the varying thickness of concrete. One-course brick lining was used in many concrete stacks, usually to a height of 10 to 15 feet.

b. Brick Stacks. Stacks of brick construction, especially those of octagon shape, were usually well designed and well built. Materials and workmanship were good. The smaller, square-shaped brick stacks, however, were generally built too light and many required bracing with angle iron or steel straps.

c. Steel Stacks. Stacks of this type, comprising the smallest number of all types observed, followed no apparent design standards. Sections of some were lap welded; others had riveted joints. The chief weakness of this type of stack lay in methods of anchorage, which were usually ineffective in safeguarding against overturning. The advantages in the use of these stacks were the economy and ease of construction and the fact that, even when knocked down, they could be quickly repaired on the ground and re-erected by crane in one piece.

2. Cause and Extent of Damage. It was considered that all damage sustained by stacks resulted from blast effects of the atomic bomb inasmuch as there was no evidence such as spalled concrete, vitrified

brick, or oxidized steel to indicate any portion of the damage was caused by fire. In both cities there were numerous apparently undamaged stacks left standing although the buildings they served had been reduced to wreckage. At Hiroshima, within a radius of 8,700 feet from Ground Zero, 15 per cent of the concrete, 50 per cent of the brick, and 70 per cent of the steel stacks were damaged to such an extent as to render them unusable without almost complete rebuilding. At Nagasaki, only four out of approximately 30 concrete stacks were damaged within 6,000 feet of Ground Zero. Two of these stacks, moreover, had been very close to high-explosive bomb hits during an attack prior to the atomic bomb explosion and it was possible that this circumstance might have contributed to the failure of the stacks. All brick and steel stacks within the same area were totally or heavily damaged. Stacks of reinforced-concrete construction proved most resistant to blast; brick was highly vulnerable; and steel stacks were the most easily damaged. The mean areas of effectiveness of the atomic bomb against reinforced-concrete, brick, or steel stacks at Hiroshima were computed to be 0.3, 2.7, and 4.1 square miles, respectively; the mean effective radii being 1,625 feet, 4,900 feet, and 6,050 feet. In view of the similarity of design and construction of stacks in the two cities, these figures should be applicable in no lesser degree to the stacks in Nagasaki. The amount of damage to concrete stacks in both Nagasaki and Hiroshima was almost negligible compared to the amount of damage to buildings within the same areas. The resistance of concrete stacks to blast effects of the atomic bomb might be attributed to a number of factors, such as structural flexibility, minimum exposed surface, fire-resistive qualities, vertical angle of blast, and, in some instances, part shielding by intervening buildings.

I. PUBLIC UTILITIES

1. General. All public services and utilities in both Hiroshima and Nagasaki sustained damage as a result of the atomic bomb attacks, and were disrupted in whole or in part for varying lengths of time. As both cities were virtually paralyzed by the sudden, widespread destructive effects of the detonations, the demand for services fell off as sharply as the supply. Despite the extent of damage and the chaotic conditions prevailing immediately following the attacks, some of the more vital services such as street railway, railroad, water, and electricity were restored to minimum levels within periods ranging from 24 to 72 hours in an effort to facilitate emergency rescue and clearance and to provide some measure of relief for the stricken populations.

2. Transportation

a. Street Railway and Bus Service. Hiroshima depended almost entirely upon the street railway system and busses for passenger transportation within the city and to outlying districts, since it contained only a small number of private vehicles. Nagasaki, having no busses, dpended heavily on its street railway system for intra-urban transportation. Its double-track system carried a daily load of 77,000 passengers.

(1) Of the 123 street railway cars in Hiroshima, 20 per cent were damaged by fire and 45 per cent by blast.

Fire damaged 21 per cent and blast 26 per cent of the motor busses. Both cars and busses were ignited by radiant heat within 1,500 feet of Ground Zero. Damage varying from total to slight was sustained by cars up to 12,500 feet from Ground Zero. Busses were damaged up to 5,500 feet from Ground Zero. In addition to the loss of rolling stock, there was a total of 11.4 miles of the overhead transmission system damaged by blast and fire. This damage included wood and steel poles and transmission cable, from 4,500 to 8,000 feet from Ground Zero. There was no damage to trackage except what was carried by bridges. Disruption of the entire electrical system resulted from fire and blast damage to converter stations as far as 6,400 feet from Ground Zero.

(2) The bomb which detonated over Nagasaki resulted in damage, both by fire and blast, to 70 per cent of that city's street-railway cars within 10,000 feet of Ground Zero, and five per cent of the total trackage. The system was further crippled by damage to 50 per cent of the trolley wire, electric power lines, and sheared and overturned steel power-line supports. It was estimated that 200,000 man hours would be required to repair Nagasaki's street railway system.

b. Railroad

(1) Hiroshima's inter-city transportation was provided by the government railroad system, comprising the double-track Sanyo Main Line, together with classification yards, repair facilities, transit sheds and stations, and a single-track line, with intermediate stations within the city, to the deep-water harbor at Ujina. The average passenger rate per month was 1,824,960 persons; average freight tonnage amounted to 9,300 tons.

(2) Railroad facilities at Nagasaki consisted of a single-track line within the city, connecting it with Tosu Junction. There were three secondary stations within the city and the main Nagasaki Station at which the line terminated. The system served primarily as transportation for passengers within the urban area and to the surburban sections.

(3) Railroad stations in both cities suffered either total or heavy structural damage from blast and fire within 7,000 feet of Ground Zero. Classification and repair facilities at Hiroshima between 8,000 and 10,000 feet from Ground Zero were superficially damaged. All communications and signal systems were either heavily damaged, or rendered inoperative because of damage to communications buildings. Rolling stock was more

heavily damaged at Hiroshima, where 13 per cent of the freight cars, 93 per cent of the passenger cars, and 75 per cent of the electric cars were damaged by blast and fire up to 6,800 feet from Ground Zero. Rolling stock at Nagasaki sustained comparatively slight damage caused primarily by blast. More important track damage occurred at Nagasaki, where crossties, ignited by flaming debris, burned intermittently for distances of 10,000 to 15,000 feet and buckled the steel rails. Further rail damage resulted through the displacement by blast of three bridges. Emergency repair work, however, permitted resumption of limited traffic after 48 hours. Although no damage was sustained by trackage or bridge crossings in Hiroshima, adjacent fires and blast debris on the tracks prevented utilization of some sections for a period of several days.

3. Wire Communications. The telephone and telegraph facilities of Hiroshima and Nagasaki sustained widespread damage as a result of the atomic bombings. One of the most serious consequences of the crippling of these utilities was the ensuing delay in organizing emergency relief and adequate rescue work in the two cities. The overhead wires and cables of the transmission systems, as a result of their exposed positions, were the hardest hit. At Hiroshima approximately 80 per cent of the overhead system was damaged by fire and blast. The damaged portion

of the system comprised over 27 miles of cable and approximately 92 per cent of a total of 7,451 wood poles carrying overhead lines. Poles were damaged by blast at 4,500 feet from Ground Zero, and burned at 6,500 feet; cable was stripped from hangers at 8,000 feet. At Nagasaki approximately 50 per cent, or 57 miles, of the aerial cables and open wires of the telephone system were heavily damaged, and 15 per cent, or 19 miles, of the open wires of the telegraph system sustained damage in varying degrees. The two exchange buildings at Hiroshima, one 2,000 feet and the other 3,300 feet from Ground Zero, were damaged and 100 per cent and 50 per cent, respectively, of the equipment contained in these buildings sustained total damage by fires resulting from short circuits. Nagasaki lost 60 per cent of its 4,891 subscribers' telephone sets as a result of the attack. The subsurface systems, comprising underground transmission cables, being the least exposed to the effects of fire and blast, suffered the smallest amount of damage. Cables and conduits were vulnerable, however, at bridge crossings and at exit points to the overhead system. Damage at these locations, although limited in extent, was sufficient to put approximately 80 per cent of Hiroshima's subsurface system out of service. Within nine days, 35 pairs of subsurface cable had been returned to service, being restricted entirely to prefectural and military needs. At Nagasaki, 10.8 per cent, or approximately 16 miles of the underground cable system was heavily damaged. As a result of the bomb effects at Nagasaki, wire communications were partly paralyzed for a week.

4. Electric Power

a. Power Supply. Hiroshima was furnished electric power by the hydroelectric plants of the Nippon Electric Company through two substations and by a steam-electric plant of the Chugoku Electric Company through seven substations. Power was transmitted by overhead lines from the hydroelectric plants to the substations at 110 kv; from the steam plant at 55 kv. The substations of the Chugoku Company transformed from 22 kv to 3.3 kv for consumer distribution, except for several large industries and the street railway company which received power at 22 kv and transformed it to their own requirements. The 22-kv distribution was transmitted by both overhead and subsurface systems. Daily power consumption in Hiroshima was 80,000 kw for lighting and 170,000 kw for heating and motor energy. The electric supply system at Nagasaki, within the area affected by the atomic bomb, comprised eight transformer stations, two switch stations, and one small generating plant. The capacity of the power transformers was 86,500 kw which supplied 40,842 residential and 949 industrial consumers prior to the attack. The majority of their transmission lines was carried on steel towers and concrete standards.

b. Damage. At Hiroshima 70 per cent of the 3.3-kv overhead and feeder system was damaged by fire and blast. Of a total of 7,000 poles in use, 4,000 wood and 27 steel-lattice poles were damaged by blast and fire, and wires were blown from the poles by blast as far as 8,000 feet from Ground Zero. Concrete poles were not damaged. Of the remaining undamaged 30 per cent of the system, only 90 per cent was usable as some sections beyond the damaged area could not be supplied with electricity due to lack of connections to substations. No damage was sustained by the 22-kv subsurface system. In Nagasaki 32.4 per cent of the 66-kv open transmission lines sustained total damage. Of 76 steel towers eight were totally damaged, and four concrete standards of a total of 30 were demolished. In addition, heavy damage was inflicted upon Nagasaki's distribution system which suffered the loss of 27.7 per cent of a total of approximately 134 miles of feeder lines; 24 per cent, or 1,491, of a total of 6,107 poles; and 27.6 per cent, or 483, of a total of 1,750 transformers. Damage to transformer substations and heavy equipment, although severe, was relatively light compared to that sustained by the overhead transmission and distribution systems. One substation at Hiroshima was heavily damaged by blast and fire 2,400 feet from Ground Zero, and another substation and a steam-electric plant, 7,700 feet from Ground Zero, were heavily damaged by fire which spread from adjacent areas. As a result of the damage to these two substations it was necessary to distribute the areas they served among the remaining substations. Four substations were slightly damaged at 5,500 feet and beyond; three substations were undamaged. At Nagasaki, three of a total of eight transformer stations sustained heavy damage to bus structures, insulators, and steel racks. Primary heavy equipment was only slightly damaged at these stations.

5. Gas Supply System. Storage facilities of the gas supply system in both cities, consisting of large gas holders, were the most vulnerable to the blast effects of the atomic bomb. The two gas holders

in Hiroshima, located 6,500 feet from Ground Zero, having capacities of 316,000 and 211,000 cubic feet, respectively, were damaged when the crowns of the tanks were torn by blast and the released gas ignited. Of the three gas holders at Nagasaki, one located 3,000 feet from Ground Zero was completely demolished by a low-order detonation after being struck by the blast wave, and the other two, 6,600 feet from Ground Zero, had their tops collapsed and sustained heavy structural damage. Total equipment damage at the producing plants was slight. The electrical switchboard and recording meters at the Hiroshima plant were heavily damaged, but there was no loss of other equipment. The retorts and producing equipment at the two coal-gas plants in Nagasaki were affected by blast only to a minor degree. Damage to mains occurred for the most part at bridges and over-crossings. Branch and feeder lines were most heavily damaged at points where they entered buildings and plants within the areas affected by blast and fire. The total effects of the damage to holders, pressure regulators, mains, and pipe lines were sufficient to disrupt completely the gas supply systems at both Hiroshima and Nagasaki, and restoration of service would have required repairs extending over a period of several months.

6. Water Supply. Both Hiroshima and Nagasaki had water supply systems that served their domestic and commercial needs and had always proved adequate for peacetime use. Hiroshima maintained a system capable of furnishing 20,000,000 gallons of filtered water a day. Water was pumped from the Ota River to a large reservoir from which it flowed to the distribution system. Pressure within the distribution system

was maintained by three booster pumping stations. Nagasaki was supplied with water from four reservoirs located within 16,000 feet of Ground Zero. There were four systems with emergency interconnections in operation, each supplied by a different reservoir. Booster stations and pumping equipment in each of the two cities were damaged only slightly; in Hiroshima, a pump motor was burned out because of falling debris, metering equipment in one station was heavily damaged, and several wood-frame buildings which housed equipment sustained structural damage; at Nagasaki, motors housed in wooden structures and the electric installation for pump equipment suffered slight damage. By far the most crippling damage was sustained by distribution pipes and mains. Mains were broken in both cities by displacement of bridges, and additional breaks in Hiroshima's mains were attributed to falling debris. There was no debris damage at Nagasaki, but failure of 12-inch mains three feet below grade occurred as a result of uneven displacement of soil caused by oblique blast pressure. The buried mains in Hiroshima were undamaged. Branch and distribution lines in both cities were heavily damaged by collapsing structures and the heat from burning buildings which melted the pipes. As a result of the damage to the mains and pipes and the consequent leakage and loss of pressure, the supply systems of both Hiroshima and Nagasaki, already taxed to the limit by wartime requirements, were rendered almost useless for fire-fighting purposes within a short period after the attack. Fire-fighting forces therefore relied principally upon bucket brigades which utilized water from domestic wells, water courses, and static tanks. After closing off the supply to those areas where leakage was greatest and to those sections where there would be no demand, sufficient emergency repairs were made within 24 to 36 hours to provide a limited amount of service to meet a portion of the populations' needs.

7. Sewer System. Although the other public utilities in Nagasaki and Hiroshima were roughly comparable in many respects to those in American cities of the same size, the problem of sewage disposal was entirely different. Human excrement was not included in the sewage, but was collected by the city from the residential areas and sold to farmers at a nominal price as a substitute for natural or artificial fertilizers which Japan lacked. The sewer systems, therefore, were maintained primarily for the disposal of domestic waste water and surface drainage. The sewer system at Nagasaki consisted entirely of open trenches and was not considered worthy of study. Hiroshima disposed of 80 per cent of its residential waste water by the use of short laterals to the Ota River; the remaining 20 per cent was carried through branch pipes to the sewer mains. Drainage waters flowed into the river through the mains which also served as storm sewers, and through open flumes. Because the height of the river prevented gravity flow during flood stages, 14 pumping stations had been installed in the system to dispose of waste and surface drainage. The equipment in six of these stations within a 5,200-foot radius of Ground Zero was heavily damaged by blast and subsequent fires at the time of the atomic bomb attack, and electric motors in two other stations which were damaged by blast were burned out as a result of falling debris. Damage to the electric

substations which powered the pump equipment rendered the undamaged stations inoperative. There was no damage to mains or flumes. Damage to the pumping stations, which was not considered serious at the time, later assumed greater significance as seasonal rains caused floods which seriously delayed repairs of other utilities in Hiroshima which utilized subsurface systems and manholes.

J. FIRE

1. Vulnerability. The cities of Hiroshima and Nagasaki were both heavily built up, with combustible buildings of Japanese domestic types predominating. Nagasaki was the more congested because of the limitations in expansion placed on it by the surrounding hilly terrain, and its streets were generally narrower. Of the 12-square-mile-built-up part of Hiroshima 68 per cent was 27 per cent or more built up (percentage of roof area to total ground area, excluding parks, fields, rivers and prepared fire breaks), whereas 70 per cent of the 3.8-square-mile built-up area of Nagasaki was 30 per cent or more built up. Probably more indicative of the greater congestion in Nagasaki is the fact that most of the population of 230,000 persons lived in an area of 3.3 square miles, compared to 245,000 persons in 9.9 square miles in Hiroshima. (Only residential areas built up more than 5 per cent were considered.) Except for one light shower in each city, the weather had been dry for a period of three weeks in Hiroshima and for ten days in Nagasaki prior to the atomic bomb attacks. At the time of the attacks, there was a southeast wind of about 2½ miles per hour in Hiroshima, and a light southwest wind (probably not in excess of 5 miles per hour)