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Subject: Report on Atomic Bomb Damage Evaluation.

Memo to Lt. Col. J. A. Derry

1. Copy Number 1 of the subject report is transmitted for delivery to Maj. Gen. L. R. Groves. This report, prepared by Dr. W. G. Penney, is entitled "A Report On the Pressure Wave Caused By the Atomic Bomb Explosion in Hiroshima and Nagasaki." Included with the report are two sets of photographs showing the damage caused in each city as well as certain specific objects and structures which were used as a basis for calculating the hydrostatic pressure and wind velocity resulting from the explosion. A key explaining the photographs is also included as well as maps of each city.

2. Copy number 2 of this report, with one set of photographs, has been transmitted to Sir John Anderson in London and Copy number 3 is in the possession of Sir James Chadwick in Washington. The final draft of this report was completed on the night before Dr. Penney's scheduled departure from London for Washington. Copy number 1 was proofread subsequent to release of copies number 2 and 3. A number of additions were made to Copy number 1 at that time so that it is the only complete copy in existence.

3. The British government would like to release this report to certain of its high policy officials but have agreed at Dr. Penney's request to limit availability of the report to Sir John Anderson, Sir James Chadwick and Dr. Penney until such time as General Groves grants approval to further distribution. It is Dr. Penney's opinion that access to the complete report should be limited to the British Chiefs of Staff. The report is arranged in such a form that further distribution of limited portions of the report could be made. Dr. Penney has requested for Sir John Anderson that General Groves grant formal approval for further distribution of the report and in form Dr. Penney of the limitations which he wishes placed on such distribution.

4. Dr. Penney has also requested that a copy of the Master report in General Groves possession be furnished to the T.A. group at the time approval for further distribution is granted.

D G Sturges
D. G. Sturges,
Capt. C.E.

2/26 - Copy of Report (photostat)
given to —
Dr. W. G. Penney
Gen. T. F. Farrell
Lt. Col. W. E. Kelley

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A REPORT ON THE PRESSURE WAVE CAUSED BY THE ATOMIC BOMB EXPLOSION IN HIROSHEMA AND NAGASAKI.

BY

DR. W.C. PENNEY

C.S.A.R.

Copy No 1 , with 2 sets of photographs Maj. Gen. L R Gro
Copy No 2 , " 1 " " " Sir John Anders
Copy No 3 , " 1 " " " Sir James Chadw

SECRET

23rd January 1946.

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Authority NND 790059

(1)

General statement

Among the observers of the Manhattan District team that went into Hiroshima and Nagasaki during September and October, 1945, was a small team to study the blast effects. The team consisted of Dr. W. G. Penney, Ensign C. T. Reynolds (U.S.N) and Dr. R. Serber. No clear programme was possible before the cities had been studied; rather, the team walked about more or less at random, until some significant feature was noticed. Notes were made, and gradually the search became organised and directed. The Report now presented is the result of a study of the notes taken jointly by all three observers, and of tests made by the writer (Dr. W. G. Penney) on samples collected during the course of the search through the two cities. Help, either in the nature of consultation, or in direct tests, has been given by:-

Road Research Laboratory, Harmondsworth

National Physical Laboratory, Teddington

Civil Engineering Department, Imperial College of Science,

Forest Products Research Laboratory, Princes Risborough,

and, of course, by the Manhattan District, which has provided excellent maps, scientific reports from Los Alamos, and assistance in the persons of Commander H. Rivers (U.S.N.) and Captain D. Sturges (U.S. Army).

Main results

The following are considered to be the main results:-

(1) The bombs performed exactly according to design in their height of burst.

(2) The bombs were placed in such positions that they could not have done more damage by any alternative bursting point in either city.

(3) The heights of burst were correctly chosen having regard to the type of destruction it was desired to cause. The extent of the blast damage was exactly that predicted.

(4) The actual tonnage of T.N.T. which would have caused the same blast damage was 5000 in Hiroshima and 20,000 in Nagasaki.

(5) The information collected would enable reasonably accurate predictions to be made of the blast damage likely to be caused in any city where an atomic bomb explosion was conceivable.

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General comparison of Hiroshima and Nagasaki

Even an intelligent observer could not at once say from inspection of Nagasaki and Hiroshima which of the two bombs was the more powerful. From some points of view, indeed, Hiroshima was worse than Nagasaki. The fire damage was much more complete; the centre of the city was hit and everything but the reinforced concrete buildings had disappeared. A few strong buildings left in a desert of clear swept charred remains was a terrifying sight. At Nagasaki, there were no strong buildings just underneath. The damage to the Mitsubishi Arms Works and the Torpedo Plant was spectacular, but not overwhelming. There was something left to see, and the main contours of the buildings were still normal.

One could stand in the centre of Hiroshima and get a view of the whole city, but this was not possible in Nagasaki, because of hills. Hiroshima was left in one's mind as a vast expanse of desolation; nothing as vivid was left in one's memory of Nagasaki.

When one came down to details, however, striking differences appeared. Trees were down in both cities, but the large trees which fell in Hiroshima were uprooted, while some of those in Nagasaki were actually snapped off. A few reinforced concrete buildings were smashed at the centre in Hiroshima, but in Nagasaki equally heavy damage could be found at 2300 ft. When one studied small things such as squashed tin cans, dished metal plates, bent or snapped poles and the like, one came to realise that the Nagasaki bomb was, in fact, much more powerful ~~worse~~ than the Hiroshima bomb. A large part of this report is devoted to explaining these details.

(3)

SECTION I: POINTS OF GENERAL INTEREST

Height of Burst: Size of Ball of Fire

Japanese army observers, watching through instruments, gave the height of burst in Hiroshima as 550 m (1800 ft), and as 500m (1650 ft) in Nagasaki.

An independent estimate was possible for the Hiroshima burst from the geometry of some flash burns on the walls in the Post Office. Pictures H 94, H 95 show the burns. An unburnt "white" shadow several feet long was clearly visible on the beaver board of a wall; the shadow was that of the horizontal parts of a metal window frame. (The shadows of the blind cord appear in the photograph, but were not useful for estimating the height of burst). Similar shadows were thrown on the beaver boards of the side walls of the bays in which two other windows of the same design were placed. From the geometry of the shape of the shadows, the position of the Post Office with respect to the point of explosion, and the orientation of the shadows and windows, Dr. R. Serber calculated that the height of burst was 1800 feet.

The shadows had distinct penumbra, the dimensions of which could be measured fairly well. Dr. Serber calculated that the size of the "ball of fire" when it was giving its maximum charring effect on the wall, was 300 feet diameter. It is interesting to note that this is much less than the maximum diameter. The time to reach the maximum charring radius is only of the order one millisecond.

Flash Burns

Telegraph poles very near the point on the ground under the centre of the explosion were often left standing. The side exposed to the flash was severely charred. By marking on a map the direction of charring, and doing this for about five or six cases, the centre of burst could be placed within about 100 feet. Confirmation of the centre was also obtained by noting the direction in which poles had been bent, or chimney stacks thrown.

At Hiroshima, flash burns on telegraph poles were visible up to a radius 9500 feet. At Nagasaki, burns were visible up to 11,000 feet.

An interesting effect was noticed in Nagasaki. The centre of burst was about central in a valley running N - S. Many trees grew on the slopes of the adjoining hills. The leaves on these trees were slightly scorched, and the general appearance of the vegetation was that of autumn. The contrast with the intense fresh green colouring of the leaves of trees in the hills further away was very striking. The autumnal appearance of the trees extended to about 8,000 feet.

Shrubs and small plants quite near to the centre in Hiroshima, although stripped of leaves, had obviously not been killed. Many were throwing out new buds.

Ground Shock

The ground shock in both ~~centres~~ cities was very slight. Water pipes still carried water, and where leaks were visible, they were mainly above ground. A few cases were found where leaks were present below ground, but the explanation was that a wall overturned in the blast, and dislocated the ground, thus breaking the pipe.

Morale Effect

The effect of the bombs on the morale of the Japanese in and around the two ~~centres~~ cities was shattering. The Japanese apparently before the two bombs were dropped, realised that they were outclassed in war but they did not realise how hopelessly until the bombs fell. The danger of radioactive contamination on the ground terrified the whole population, and had resulted in only spasmodic attempts at clearing debris.

Blast Damage to Human Beings

While the analysis of the medical side lies completely outside our province, two comments seem worth making. The first is that the pressures developed on the ground were not sufficient to kill by straight compression more than those people very near to the centre (approximately a radius 1500 ft in Nagasaki, and not at all in Hiroshima). On the other hand, the tremendous drag of the wind even up to distances of the order of 1 mile must have resulted in many multiple fractures and deaths. Picture N 90 perhaps illustrates the point. Large pieces of the prison wall were flung 80 feet. Probably some of them went 30 feet high before falling. The chances of a human surviving such treatment are probably small.

Fire Damage

The fire damage in both cities was tremendous, but was more complete in Hiroshima than in Nagasaki. The effect of the fires was of course profoundly to change the appearance of the cities, and to leave the central parts bare, except for the reinforced buildings, and objects such as safes, chimney stacks and pieces of twisted sheet metal. However, no special significance was attached to the fire damage, since it was a property more of the cities themselves than of the bomb.

No large fires were started instantly by the bomb. Straw, and many grass mats which were hanging outside to air, were ignited immediately and no doubt some fires were started in this way. A more likely cause were the charcoal braziers, one of which was to be found in nearly every house. Some trees were ignited by the heat of the explosion. Picture H 93 shows a clear case of the flash ignition of a tree.

Many peculiar effects due to "fire winds" were observed by the Japanese, but were not recorded very accurately. One "twister" in particular ~~thread~~ threw people into one of the rivers at Hiroshima. Wind velocities up to 50 f/sec (a low figure, probably often exceeded) were recorded, compared with 6 f/s before the explosion.

Heavy fire damage extended about 8000 ft S of X in Nagasaki, and to about 6000 ft circularly about X in Hiroshima.

Several isolated fires were found in both cities up to 9000 ft where the cause was clearly a brazier or something similar inside the building. Sometimes a hill protected the building from flash burn; sometimes a large building, and the ~~euase~~ cause could not have been flash ignition of some tinderlike material.

The most remarkable escape from fire damage was the Torpedo works at Nagasaki. The whole framework was wood, but there was no fire in the main factory. Several small sheds (the paint shed in particular) did catch alight and were completely burnt out.

Long Range Blast Damage

There was no consistency in the long range blast damage. One would think that one had reached the limit, and then 2000 ft further away would find further evidence of damage.

The most impressive long range damage was the collapse of some of the barrack sheds at Kamigo, 23,000 ft S of X in Nagasaki. It was remarkable to see some of the buildings intact to the last detail (including roof and even the windows) and yet next to them a similar building collapsed to ground level.

The limiting radius for severe displacement of tiles in Nagasaki was about 10,000 ft, although isolated cases were found up to 16,000 ft. In Hiroshima, the limiting radius for severe damage to tiles was about 7000 - 8000 ft. However, even at KAITCHI, distance 26,000 ft, some tiles were displaced. (Possibly these were the results of the typhoon and not the atomic bomb)

The Mach Y

Only by a coincidence would it have been possible to detect any evidence of the variation of pressure up the stem of the Y. There was a very large chimney stack in the Mitsubishi Arms Works, 3,500 ft S of X. The chimney was badly cracked, but more interesting to us was a steel ladder running from top to bottom. The stack was at least 120 ft high. The ladder was bowed between the supports, which were at about 8 ft centres. No variation with ~~weith~~ height in the bowing could be detected. The reason was that the ladder had bent as far as it could without stretching. The shock at the rivets had all been taken up, and to produce any further distortion a very considerable force would have been required.

The ladder was not suitable for estimating ~~extending~~ the peak pressure, because the air flow was very largely controlled by the chimney, and there seemed no accurate way of allowing for this.

At Mogi, a distance of seven miles, over steep hills at least 600feet high, about 10% of the glass came out. In nearer sequestered localities only 4 miles from the explosion, no damage of any kind was caused. An interesting effect was noticed at Mogi. Eye-witnesses said that they thought a raid was being made on Mogi. One big flash was seen, then a loud roar, followed at several second intervals by half a dozen other loud reports, from all directions. These were obviously reflections from the hills surrounding Mogi.

(7)

Shielding Effects

Because of the great height of burst, one would not have expected to find any evidence of shielding of one building by another, at least up to a radius 2,000 - 3,000 ft. It was in fact difficult to find any evidence at any distance of such shielding. One might perhaps say that there was a little shielding of the building behind the Administration Building of the Torpedo Works by the Administration Building itself, but the effect was very slight. There was also some evidence that the group of buildings comprising the Medical School in Nagasaki did afford each other mutual protection. On the whole, however, shielding of one building by another was not noticeable.

Hills were effective in giving shielding, but only at such distances that the blast was becoming critical for the structure. Houses built in ravines at Nagasaki pointing well away from the centre of explosion survived unscathed, but other at similar distances in ravines pointing towards the centre were unduly damaged. To the north of the Torpedo Works was a small hamlet 8,000 ft from the centre. One could see a distinct variation in the intensity of damage acrossthe hamlet, corresponding with the shadow thrown by a sharp hill.

The best example of shielding by a hill was in the S E direction from the centre. The damage at 8,000 ft to buildings approximating to the European type was mostly light C, namely 50% of windows and light plaster damage. These buildings were on the reverse side of a steep hill (Suwa Park) At the same distance to the S.S.E. the damage was heavy C to light B, namely all windows and frames, doors, heavy plaster damage and a few cracks in the brickwork. The contrast may be illustrated by the fact that at the Prefectural Office in S.S.E. at 10,800 ft the damage was bad enough for the building to be evacuated, while at the Nagasaki Normal School (see picture N. 101) to which the Prefectual Office had moved, the damage was only D, or very light C.

There was one other peculiar type of shielding, best exhibited by the workers houses to the N of the Torpedo Plant at Nagasaki. These were 6,000 - 7,000 ft N of X. The damage to these houses was nothing like as bad as in those 1,000 ft further away. It seemed as if the great destruction caused in the Torpedo Plant had weakened the blast, and the full power was not restored for another 1,000 feet or so.

Radii of A, B and C Damage.

It is customary when describing the damage caused by a bomb, to give the radii of A, B and C damage. Useful though these radii have proved to be, it is not thought that they are very significant for an atomic bomb. The height of burst must be chosen for a particular purpose; if this is achieved, the concomitant damage is relatively unimportant. However, the type of damage caused by the Nagasaki bomb over level ground may be described as follows.

(1) Window damage complete to 12,000 ft; some damage up to 40,000 ft or even more.

(2) Plaster damage (ceiling and walls) very heavy at 9,000 ft, moderate at 12,000 ft and ~~absent~~ light at 15,000 ft.

(3) Roof damage to slate or tile, heavy at 10,000 ft, light at 15,000 ft. ~~In~~ Sheet metal roofs, depending on quality and orientation, ~~but~~ approximately the same as for slate or tile.

(4) Window frames and doors. Heavy at 8,000 ft, light at 12,000 ft.

(5) Nine inch brick wall surburban house. Walls cracked heavily at 5,000 ft, some cracks at 6,000 ft, few cracks at 7,000 ft. Untouched at 8,000 ft.

(6) Reinforced concrete buildings, 10" walls, 6" floors and 4" roof, two or three stories, ~~completely wrecked~~ badly damaged but still standing up to 2,000 ft. Minor structural damage at 4,000 ft.

(7). High quality steel frame building. No damage to frame but panels blown in up to 1500 ft.

(8) Churches of brick, 18" walls to accommodate 1,000 people, completely destroyed up to 3,600 ft. With 12" walls, ~~completely destroyed~~ were all cracked up to 6,000 ft., roof probably collapsed and blown off.

(9) Gas holders dished in up to 7,000 ft.

9

SECTION II: METHODS OF ESTIMATING THE PEAK PRESSURE

While the cities of Hiroshima and Nagasaki were being explored, several independent possibilities were always kept in mind for spotting something which would provide an estimate of the peak pressure. Naturally, in the course of time, experience was gained, and the search for likely objects became highly selective. From this point of view it was unfortunate that Nagasaki was visited before Hiroshima. There was a great wealth of data in Hiroshima, in remarkable contrast with the scarcity in Nagasaki. In the latter city for example, we were unable to find a single flagpole or lightning conductor just bent over by the wind of the explosion; in Hiroshima, we had the choice of about twenty. If our visits to the two cities had been in the reverse order, we might have missed a few of the observations actually made in Hiroshima but this loss we could well afford: on the other hand, we might have gained two or three more reliable figures for Nagasaki, and thereby improved our estimates of the tonnage in this city.

Principles of the Interpretations of the Observations →

We explain the principles underlying the interpretations of observations which led to estimates of the peak pressure. The numerical results are given later in this section.

Crushed Metal Cans

One of the simplest methods of estimating the peak pressure was from the crushing of oil drums, gasoline cans or any other empty thin metal vessel with a small opening. The assumption here made is that the blast wave pressure came on instantaneously, the resulting pressure on the can was more than the case could withstand, and the walls collapsed inwards. The air inside was compressed adiabatically to such a point that the pressure inside was less by a certain amount that the pressure outside, this amount being the pressure difference outside and in that the walls could stand in their crumpled condition. The uncertainties involved are first, that some air rushes in through any opening that the can may have, and thus help to build up the pressure inside; and second, that as the pressure outside falls, the air inside cannot escape sufficiently fast to avoid the walls of the can being blown out again to some extent. Both uncertainties are such that estimates of pressure based on this method are on the low side, i.e. they are underestimates.

Let V_o be the initial volume of the can, V_c its crushed volume, and P_c psi the mechanical strength against crushing in the collapsed position. Then the peak pressure P is taken

$$P \geqslant P_c + p_o\left[(V_o/V_c)^{\gamma} - 1\right] \qquad (1)$$

where $p_o = 14.7$ psi, that is atmospheric pressure, and $\gamma = 1.4$ is the ratio of the specific heats of air.

The percentage loss of volume is $100(1 - V_c/V_o)$, and for convenience and use in this report we have plotted in Figs. 1 and 2 the rise in air pressure inside a can, namely $p_o\left[(V_o/V_c)^{1.4} - 1\right]$ in pounds to the square inch against the percentage loss in volume. Also given is the compression ratio V_o/V_c. For example, from Fig. 1, it is seen that the rise in air pressure corresponding with a 20 per cent. loss of volume is 5.3 psi.

It is worth pointing out that a drum or tin can can withstand for a short time considerably more than its critical static crushing pressure. The sides give way because of instability, and the instability requires time to grow. Consequently, one might sometimes find cans intact at places where the peak pressure was higher than the static strength of the can. If, however, the can did give way, the amount of distortion would normally be considerable, because the strength drops rapidly ~~considerably~~ once dents have appeared. One can easily see by a simple calculation that the time required for a small dent to grow to a large one is very small. For example, if a dent has been established, and there is an unbalanced pressure on the two sides of the dent of 1 psi, the acceleration is very large. If the thickness of metal is 0.020-inch, then the pressure 1 psi moves the metal 2 inches from rest in five milliseconds.

Insert paragraph on other side of this sheet.

A modification of the crushed tin can is the crushed metal tube. Many examples of this were found, but not a single one of much quantitative significance. The best perhaps, was a rectangular copper drain pipe near the Shin Aioi Bashi in Hiroshima. However, even for this, the sample brought back for test indicated a peak pressure 35 psi where the true value was nearer 20. Pipes suffer from two disadvantages. The first is that the pipe does not crush equally along its length; unless one could get an estimate of the loss of volume along the entire length, often as much as 20 feet, one could not tell what the pressure inside was. Often, the pipe was not air tight, thus making any estimate impossible. The second disadvantage is that the pipe

The mode of collapse (in a blast wave), and the speed at which collapse occurs in the various harmonics, are interesting questions which the writer has not yet had the opportunity to consider. The critical load which causes collapse, and the mode of collapse of cylindrical shells have been considered by Southwell and others (see Love's Elasticity). The observations made on collapsed drums and cans agree with theory to this extent, that the short fat cylinder (40 gallon gasoline Japanese and British drums) collapsed on the $n=3$ harmonic, while the long thin cylinder (the paper containers in the City Offices, Hiroshima) collapsed on the $n=2$ harmonic.

is vulnerable to the wind pressure; the pipe either strips off in the wind, or changes volume sufficiently to make estimates of the peak pressure quite unreliable. A good example of the tremendous force of the wind in the Nagasaki explosion is shown by the thin sheet metal drain pipe on the walls of the Administration Building of the Mitsubishi Torpedo Works, 4050 feet from X. Picture N56 shows this pipe, crushed by the initial peak pressure and then whipped about in the wind.

Visual Estimates

It proved possible to make one or two absolute estimates of the peak pressure, as well as several comparisons between Nagasaki and Hiroshima simply by inspection of the nature of the damage. Comparison was also made with the damage at the Macdonald Ranch in New Mexico, caused by the Trinity Explosion.

Membranes, Plates and Panels

Paper Panels

Knowing that the Japanese workers homes use many paper panels as partitions, much was hoped for in the way of getting the critical distance at which these panels failed. However, our luck in this respect was poor. At Nagasaki, we thought we had found a beautiful example at the Kamigo barracks, 26,000 feet to S of X, but on checking with the householder, we discovered that the "damage" was caused by a "small boy". The panel had been exposed "side on" to the blast. The bottom panels were gone; these of course were the ones which the child could reach. The upper panels were intact. The panels could stand about 0.5 psi, (see later in the Tests Section) and hence the peak pressure was not more than this. From the collapse of a wall supported by rather flimsy wooden uprights we estimated that the peak pressure was greater than 0.4 psi. Hence we have a good bracketing of the peak pressure here.

One almost perfect example of the failure of paper panels was found 12000 ft. ESE from X in Hiroshima. The owner of the house exaplined exactly how the paper screens were at the time of the explosion. They were "side on" within 1°. He was indoors and saw the panels blow in, and with it, the whole framework carrying the panels. About 80 per cent. of the paper panels had torn. The rest were intact, and half a dozen pieces were brought back for test.

(R)

Metal sheets

Two good examples of the dishing of a metal sheet were obtained, one in Hiroshima and one in Nagasaki. The interpretation of the observations on the dishing of metal plates can apparently only be done with the aid of experiment. The theory of the elastic plastic behaviour of a metal plate firmly clamped at the edges is known from the work of Kirkwood and Taylor, but the corresponding problem for freely supported edges has not been considered. There is of course, a pronounced difference in the magnitude of the forces needed to cause a bend in a metal plate with no stretching of the surface, and those to cause a dishing, with the accompanying stretching of parts of the plate.

An old safe, of poor construction compared with modern standards, 200 feet from X in Hiroshima, was dished in 4 inches. The central long edge was free; the two short edges were simply supported except for the two hinges. A model was made of this safe door and tests indicate that the peak pressure was probably about 35 ~~50~~ psi.

A well-made tool cabinet was found at Nagasaki 2300 feet from X. The top had dished in $\frac{3}{4}$-inch. In my preliminary report, an incorrect assessment was made of this observation; the proper way to treat the problem is given in the Tests Section, and gives the peak pressure as probably about 30 psi.

Glass Panel

About one half of the glass panels of a mail-chute 600 feet from X at Hiroshima were broken by the hydrostatic pressure of the blast. A fairly good ~~However, no very accurate~~ value can be obtained from this observation; ~~except tha~~t the peak pressure was between 20 and 30 psi, and the probable value was 25 psi

Concrete Panels and Air Tight Spaces on Reverse Side

Five examples were found of a reinforced concrete panel or slab yielding under the hydrostatic pressure of the blast. In each case, the pressure on the reverse side was practically unaffected. The examples are, (1) Floor of bank 250 feet from X in Hiroshima: (2) Side wall of basement in Chamber of Commerce Hiroshima 1000 feet from X: (3) Floor of Radio Station Hiroshima

3100 feet from X: (4) Wall panels of Transformer Station Nagasaki 3400 feet from X: (5) Floor of Administration Building, Mitsubishi Torpedo Works, Nagasaki, 4050 feet from X.

Of these (4) was of little value, because the pressure was much beyond critical. All the central portions of the panels had been torn away, and the edge were pointing inwards at 30°. Panel (2) was a very good example and gave a reliable figure. Panel (3) was valuable, not so much because it gave a good value, but because it was very similar to Panels (5). The pressure on (3) could be very closely determined from evidence of other types (most precisely from the bending of flagpoles); and thus a simple and small correction gave a most valuable point for panel (5) in Nagasaki.

The details of (1) - (5) are given later in the Tests Section.

Wooden Floor

Another variation on the failure of a panel was found in the telephone exchange 3800 feet W of X in Hiroshima. The joints in one panel of a wooden floor, covered by mats, failed. The floor was taken up and its construction noted. Quite a good value was obtained for the peak hydrostatic pressure in this building.

Barrack Walls and Wall of a Timber Store Barn

The wooden supports of a practically airtight barn in Hiroshima, and the wooden supports of the walls of two buildings in the Kamaigo barracks at Nagasaki broke under the hydrostatic pressure of the blast. From the details of the construction, estimates of the peak pressure were made.

Drag Problems

An interesting series of observations was made on the bending of steel flagpoles and lightning conductors in the wind from the explosion. Similar problems were the bending of steel ladders, the snapping of telegraph or power line poles and the failure of smoke stacks.

The drag on an object of area A in an air stream of density ρ and mass velocity u is by definition FA, where

$$F = \tfrac{1}{2} C_D \rho u^2 \qquad (2)$$

and C_D is the drag coefficient. For a pipe of diameter D and length L exposed perpendicularly to the wind we have

$$A = DL$$

The drag coefficient is a function of the Reynold's number R for the particular values of D, ρ, and u.

$$R = \frac{Du\rho}{\mu} \qquad (3)$$

and μ is the coefficient of viscosity of the air, at the density and pressure prevailing.

Values of C_D have been measured in various wind tunnels. It has been found that C_D depends to some extent on the "roughness" of the surface. A pipe 1-inch diameter whose surface has been covered with carborundum powder sometimes gives as much as twice the drag as one whose surface has been highly polished. Of course, these are extreme limits, and in the examples with which we are concerned, the drag coefficient can usually be estimated within 10 per cent. The deduction of the value of u, and hence of the peak shock wave pressure leads to a value with an error of not more than 3 per cent. due to the uncertainty in C_D.

The bending moment at the base of a vertical pole subject to the horizontal air stream V is

$$M = \tfrac{1}{2}DL^2F \qquad (4)$$

This is to be equated to the yielding bending moment of the pole.

If the pole is a tube of outer and inner radii a and b, and T is the yielding tension of the material, then the yielding bending moment M is

$$M = 4T\,(a^3 - b^3)/3 \qquad (5)$$

Alternatively M can be measured by experiment. Thus, a piece of a steel tube flagpole from Hiroshima was brought back and M measured directly. The agreement with formula (5) was very close, assuming a value for T of 20 tons/sq,inch.

In the case of telegraph poles, samples of the wood from poles at Nagasaki were brought back for identification, and the value of M for a standard pole of 8 inches diameter was provided by the Forest Products Research Laboratory at Princes Risborough.

Now it is necessary to consider a correction that sometimes had to be applied because the yielding of the pole was more than could be called "just critical".

(15)

If I is the moment of inertia about the base, the equation of motion while yield is occurring and the pole is accelerating is

$$I\ddot{\theta} = \tfrac{1}{2}DL^2F(t) - M \qquad (6)$$

The acceleration drops to zero when the right hand side vanishes. The momentum of the pole then carries the pole further, and the acceleration is negative. The equation of motion in this phase is

$$I\ddot{\theta} + \tfrac{1}{2}DL^2F(t) = M \qquad (7)$$

The motion stops when $\dot{\theta}$ reaches zero again. The bending moment due to the weight of the pole has been neglected. This is a satisfactory approximation, since it is a small correction to a correction.

Since we are concerned only with the motion near the peak of the pressure wave, we may write

$$F(t) = F_o - kt \qquad (8)$$

With this simplification, the accelerating phase and the decelerating phase are symmetrical, and the displacement at the end of the accelerating phase is just one half of the final displacement, and $\ddot{\theta}$ is zero at the central position.

Solving the equation for the accelerating phase subject to the conditions

$$t = 0 \quad \theta = 0 \quad \theta' = 0,$$

and writing ϕ for the observed final displacement, reached at time T we find

$$\left.\begin{aligned} T &= (2F_o/k) - (4M/DL^2k) \\ F_o &= (2M/DL^2) + (12I\phi/DL^2T^2) \end{aligned}\right\} \qquad (9)$$

We write

$$F(t) \; \cancel{F(t)} = F_o\left(1 - \frac{2\delta u}{u_o}\right) \qquad (10)$$

where δu is the change of mass velocity in the time t which has elapsed since the shock wave struck the pole.

Now insert the Riemann relationship for the motion behind a plane shock

$$\delta u = 5(c - C) \qquad (11)$$

where c is the velocity of sound at the pole, and C the velocity of sound just behind the shock when it strikes the pole.

Substituting the Rankine-Hugoniot equation for u_o, and making some very close approximations, it is found that

$$F(t) = F_o\left[1 + \frac{2\delta p}{P}\sqrt{\frac{p_o}{p_o + P}}\right] \qquad (12)$$

where p_o is atmospheric pressure, ~~and~~ P is the shock overpressure, and δp is the change in pressure in time t.

The detailed shapes of the pressure-time curves at various radii are not known accurately for air burst high explosive charges. However, the peak pressure and positive impulses are known fairly well. For our purposes, we may write with sufficient approximation

$$P = P_0 (1-\alpha t). \qquad (12)$$

We must consider how the best choice of α may be made. Our applications are directed towards estimating corrections to the peak pressure from observations or drag problems involving a finite amount of yield. Possibly the first half of the area of the positive pressure-time curve is involved. We decided that the most suitable method of estimating α was to use (12) and choose α so that the positive impulse I had the proper value.

Hirschfelder, Littler and Sheard (LA 316) have given the best estimates possible for the peak pressure and positive impulse from large charges burst on or near the ground. Their figures are adopted, but modified in the following way. It is known that up to an optimum height air burst charges give larger peak pressures and larger impulses at ground level than do charges at ground level; furthermore the positive impulse for a given peak pressure level is also greater. Therefore we take Hirschfelder, Littler and Sheard's figure for positive impulse against peak pressure, and add 15%. In this way we believe we have a good approximation to the best values. The table below has been constructed in this way. The figures 5000 tons and 20,000 tons have been chosen as appropriate, since the data before the present type of correction has been applied indicate that these are the equivalent tonnages for Hiroshima and Nagasaki. The values of I correspond with 5,000 tons; α is given for 1800 ft. air burst of 5,000 tons and 20,000 tons.

TABLE I

P p.s.i.	6	8	10	16	20
I p.s.i. sec	1.41	1.61	1.78	2.20	2.44
1.15 I	1.62	1.85	2.05	2.53	2.81
(5000^T)	1.85	2.16	2.44	3.16	3.56
(20000^T)	1.16	1.36	1.53	1.99	2.25

~~then~~ To the order of magnitude in which we are interested in equation (12),

$$\delta p/P = \alpha t,$$

and

$$F(t) = F_0 + 2\alpha t F_0 \left[P_0/(P_0+P) \right]^{\frac{1}{2}}$$

Referring back to (8), we see that

$$\left.\begin{aligned} k &= 2\alpha F_0 \left[P_0/(P_0+P) \right]^{\frac{1}{2}} \\ T &= \frac{1}{\alpha} \sqrt{\frac{P_0+P}{P_0}} \left(1 - \frac{2M}{DL^2F_0}\right) \end{aligned}\right\} \quad (14)$$

where F_0 is given by (9).

Overturning of Memorial Stones.

For simplicity, we shall consider only the case where the blast is normal to one of the faces. If a stone was actually overturned by a blast not normal to a face, then the estimated peak pressure is greater than that calculated by the method given below.

One difficulty in applying observations on overturning of stones to estimate the blast is uncertainty in the amount of "stiction". The blast does its work very quickly, and it is not quite clear that the hydrostatic pressure on the exposed faces is the same as that in the air cavities under the base. No doubt, variations in the data on any one type of stone in a shrine may to some extent be attributed to a variable stiction, but the variations were surprisingly small. A second difficulty was that one could not always be sure that a stone had overturned and not slipped. By applying a push at the half height, one could usually decide that the stone would overturn under a steady push much more easily than it would slip. An impulse however might well cause slipping rather than overturning; certain large stones of mass 800 - 1000 lb. and of cubical shape had certainly slipped.

The examples ~~given below~~ chosen were almost certainly cases of overturning. Usually the stones were inset into a little hollow, effectively preventing slipping.

Stones of almost the same dimensions as the ones ~~given~~ selected were overturned forwards; probably the stone nearly toppled, swung back and the reverse wind of the suction phase toppled it the other way.

Just as with telegraph poles, chimney stacks and other objects affected by the wind, there was a region near X (about 2,000 ft radius) where the blast wave was not a simple vertical one, running horizontally. One can do little with theory in the central region, and we therefore confine ourselves to observations further out.

The theory of the overturning of a rectangular stone in a blast wave leads to some differental equations which could only be accurately solved by numerical methods. However, the data do not justify an elaborate investigation and we made some reasonable approximations.

Let θ be the angle between the vertical and the line joining the centre of gravity to the turning edge. Let I be the moment of inertia about this edge, M the mass of the stone, Z the height and X the length of the side of the base not the turning edge. The width of the stone does not enter, except finally in the Reynolds number, and we omit this, assuming effectively unit width. Using absolute units, the equation of motion we approximate by

$$2I\ddot{\theta} = -FZ^2 + MgZ\theta \qquad (15)$$

where F is the drag pressure per unit area as a function of t. Writing as we did before in the equation of motion of the plastic yield of a rod

$$F = Fo - kt,$$

the equation of motion then integrates. The boundary conditions are

$$t = 0 \quad \theta = X/Z, \quad \dot{\theta} = 0$$

The solution is

[illegible]

$$\theta = \left(\frac{X}{Z} - \frac{ZFo}{Mg}\right)\cosh mt + \frac{ZFo}{Mg} + \frac{Zk}{Mg}\circlearrowleft\left(\frac{\text{simhmt}}{.m} - t\right) \qquad (16)$$

$$\text{where} \quad m^2 = 3g/2Z \qquad (17)$$

To avoid transcendentals, and with accuracy equivalent to that used in writing the equation of motion, we expand θ as a power series in t, up to terms in t^3.

If the stone is to topple, θ must reach the value zero, and the critical condition is that θ just reaches the value zero with zero velocity i.e. $\dot{\theta} = 0$ where $\theta = 0$

Doing the algebra, it appears that the time T to reach the toppling position is

$$T = \frac{2Mg}{Zk}\left(\frac{ZF_o}{Mg} - \frac{X}{Z}\right) \qquad (18)$$

where M is the mass.

The value of Fo obeys the relationship

$$F_o = \frac{MgX}{Z^2} + \left(\frac{Mk^2X}{Z}\right)^{1/3} \qquad (19)$$

Writing M = ρ XZ, and using the expression (14) for k, we have finally

$$F_o = \frac{\rho g X^2}{Z} + \left(\frac{4\alpha^2 X^2 F_o \rho p_0}{p_0 + P}\right)^{\frac{1}{3}} \qquad (20)$$

This may be used as the basis of an iterative process to determine Fo.

The procedure we adopt is to use the known tonnage to select the proper values of P and α for a shrine in Hiroshima. Then we may calculate the drag coefficient from the above equations. Using this coefficient, we then proceed to the Nagasaki results to ~~get~~ estimate the peak pressure ~~at 1600 ft.~~ there.

(19)

COMPRESSION OF OIL DRUMS AND TIN CANS

This method, the principles of which have been described earlier, proved to be satisfactory and somewhat better than might have been anticipated. The method, of course, is not usually to be regarded as comparable in certainty with that based on the bending of a metal pipe.

We now give a series of observations in both Hiroshima and Nagasaki. The loss of volume due to compression was measured for the "blue-print container" with much greater accuracy than was possible in the other cases, because this particular drum was brought back for test. In other cases, the loss of volume was estimated with good accuracy from measurements made on the drum or can. This was possible for containers of rectangular cross section, but failed for those of circular cross section. However, we discovered by actually trying out the idea, that visual estimates could be made with surprising accuracy. Eight various drums of circular cross section were crushed by reducing the pressure inside until collapse occurred, and in most cases we made a visual estimate of the loss of volume. The loss of volume ranged from 15 per cent. to 35 per cent.; there is a remarkable difference in the appearance of drums at these two extremes. Drums were divided into classes, according to whether the loss of volume was 10-15 per cent., 15-20 per cent., 20-25 per cent., 25-30 per cent., 30-35 per cent.. There was no difficulty in placing the drums in the right class, especially after we had measured two or three. Two of the observations given below are based on a visual estimate of the loss of volume from photographs of drums of circular cross section.

Test of the hypotheses

The hypotheses were that on collapse the air was compressed adiabatically, and that the pressure difference between outside and inside was the collapsing pressure of the drum in the collapsed position. Two tests, one a repetition of the other, were made to see if these were justified, and the tests were successful.

The drums used were standard British petrol drums 32⅛" high, 22¼" diameter, thickness 0.048". There were two main ridges, with four small ones in each of the three sections. Most of the Japanese drums were exact copies of these in all respects.

A hyvac suction pump lowered the pressure inside slowly with pauses for equalisation of temperature; at collapse, the pressure inside was read by a mercury manometer connected to the inside. The volume in the collapsed position was measured. The drum was evacuated further until it again collapsed. The second collapse was gradual, in contrast to the first which was "sudden". The first collapse, however, was not so fast that one could not follow it by eye; at a rough guess, the collapse took one quarter of a second. Collapse on the n=3 harmonic.

Atmospheric pressure	752 mm.
First collapse when pressure inside was	295 mm.
Pressure just after collapse	505 mm.
Volume before collapse	206,400 c.c.
Volume after collapse	143,100 c.c.

Second collapse at 483 mm.

It was, of course, not possible to get the manometer reading instantly after collapse, because the mercury bounced about; the pressure inside was in the region of 30 cm., but was falling slowly, due to the cooling of the air inside. In view of this slight uncertainty we may say that

(1) the compression ratio was 1.44, and the pressure inside at collapse, namely 295 mm., should have risen to 495 mm., compared with 505 observed.

(2) the pressure outside, after first collapse, namely 752, should equal the pressure estimated inside, namely 495, plus the strength in the collapsed position, namely 269.

The agreement is very close. A second test gave results very similar to the one described above, and are not quoted here.

Blue-print container, Hiroshima

~~This was a somewhat disappointing example because there seems no doubt that the results are in error, unless some reservations are made.~~ A blue-print container, shown in H 77 , of excellent construction, had a nicely fitting lid for a large opening at the top. The lid, which had a rubber washer round it, was cramped into position with a lever on the handle. The container was practically airtight in the compression of the blast wave; as the pressure outside fell, the lid blew open, leaving the container, it was hoped, in an exact register of the peak pressure.

The container was found in the Communications Bureau 5000 ft. E.N.E. of X in Hiroshima. In all, there were four containers and one was brought back for test. The three which were discarded had burnt papers in them, but the one which was selected was clean and empty. There may, of course, have been papers inside at the time of the explosion, and these had been removed before we found the container. In that case, the compression ratio would be greater than that measured in the text, because the papers would act as practically incompressible.

The metal lever catch was badly bent, due to the compressed air inside pushing up the lid with considerable violence as soon as the external pressure fell. ~~It would seem as if~~ Perhaps the sides of the container were also partly blown out at the same time.

The results were as follows:

Original volume	57125 c.c.
Volume in collapsed state	51525 c.c.
Loss in volume	9.8 per cent.
Adiabatic pressure developed	2.28 p.s.i.
Further collapse in collapsed state at 4.2 cm. Hg =	0.81 p.s.i.
Peak pressure in blast	3.1 p.s.i.

Hence we have

$$P = 3.1 \text{ p.s.i. at } R = 5000 \text{ ft.}$$

Comparison with the peak pressure estimated at distances 4000 - 5000 ft. shows that the present value is a little low. The following are possible reasons:-

(1) The container was in a strong building and the pressure inside may not have reached the outside value, at the place where the container was situated (unlikely),

(2) The walls of the container may have partly blown out before the lid gave way (most probable),

(3) The container may have contained numerous papers at the time of the explosion (possible).

Crushed can, Nagasaki

A crushed can in one of the furnace buildings of the Mitsubishi Arms works 3800 ft. S. of X gave a reasonably accurate value for the pressure. The can is believed to be the one appearing in N 7.

From measurements made on the can, the compression ratio was estimated at 1.53 (or the loss of volume was 35 per cent.). The adiabatic air pressure reached inside the can was 13 p.s.i. Adding 1 p.s.i. for the strength of the can, we have

P = 14 p.s.i. at R = 3800 ft.

Crushed can, Hiroshima

The can shown in H 68, 4100 ft. S. of X in Hiroshima, was estimated from measurements on the can to have a compression ratio 1.22 (or the loss of volume was 18 per cent.). The adiabatic pressure was 4.65 p.s.i. Adding 0.85 p.s.i. for the strength of the can in the compressed state (the metal was very thin) we have

P = 5.5 p.s.i. at R = 4100 ft.

Crushed gasoline drum, Hiroshima

The crushed gasoline drum appearing in H 46 and H 25 was estimated visually to have suffered a loss of volume 35 per cent. (compression ratio 1.53). The adiabatic overpressure was therefore 13 p.s.i.. This drum was similar to those tested in the laboratory, except that the drums tested had four small ridges in each of the three sections separated by the large ridges. We found that drums with a compression similar to the one now being considered were able to withstand about 9 p.s.i., and that in the crushed state were able to withstand 5.5 p.s.i.. Reducing this to 5 p.s.i. to allow for the somewhat weaker construction we have

P = 18 p.s.i. at R = 900 ft.

Critical limits for the crushing of four-gallon cans, Nagasaki and Hiroshima

There were very many four-gallon gasoline cans 9 x 9 x 13.5" in Nagasaki and Hiroshima. The metal thickness was nearly always 0.013": four samples all agreed at this value.

The maximum distance at which the cans had collapsed in Nagasaki was 8000 ft., and in Hiroshima was about 4500 ft.. However, a curious observation was made. If a can had failed at all, it had failed to a considerable extent. One could, for example, find two similar cans next to each other, one of which had collapsed about 10 per cent. or a little more and the other had not collapsed at all. A 10 percent loss of volume corresponds with an adiabatic pressure 2.4 psi. Adding 1.0 psi for the strength in the crushed state gives us P = 3.4 psi at R = 8000 ft in Nagasaki

Crushing of a rectangular drainpipe, Hiroshima

This is not a satisfactory observation, and almost certainly gives a value which is too high. However, the details are given because they are interesting, and justify to some extent our decision not to pursue this method of estimation.

Most of the drain pipes for carrying rain water from the roods of the larger buildings in Japan are thin sheet metal pipes of very cheap and flimsy construction. Some are made of copper and some of galvanised sheet iron. One of the better type of copper pipes was found on the reinforced concrete building next to the Shin Aioi Bashi in Hiroshima, 1000 ft. W. of X. The particular building appears in H 26 where the drain pipe is also seen. A section of this pipe was taken as a sample; the distortion of the cross section was not quite the same over the whole length of the pipe, but it was thought that the sample was a fair average.

Figure 4 gives a tracing of the cross section. The area of section was measured with the aid of a planimeter and found to be 1.93 in.^{2}. The original dimensions were found by straightening the metal and measuring them; the internal dimensions were 1.78 x 2.38 in. Hence the compression ratio was 2.20. The air pressure inside the pipe, from Figure 2 therefore rose to 30 p.s.i. above atmospheric.

Now we must assure ourselves that the wind pressure was not enough to crush the pipe, after the pressure inside and out had become approximately equal. By testing the section, we estimated that about 5 p.s.i. were necessary to cause further distortion. This is far in excess of the wind pressure. The maximum hydrostatic pressure in the blast, according to this observation, is 35 p.s.i.

P = 35 p.s.i. at R = 1000 ft.

As explained above, this is an incorrect result; the cause of the error must be that the pipe was not crushed uniformly over its whole length.

PANEL PROBLEMS

Paper panels at Hiroshima

Two light paper and bamboo screens 12000 ft. S.E. by E. from X in Hiroshima happened to be in position in a building at the time of the explosion. The screens were within 1° of the "side on" position. Most of the panels had failed, but about 20 per cent. were intact. The individual panels were 6" x 3½". Some of the paper was brought back for test.

It was not possible to make a satisfactory panel on the full scale, and therefore half scale was chosen. The paper was mounted between two wooden clamps, each with a hole 3" x 1¾". One of the clamps was the end wall of a box, running from which were two tubes, one to a Hyvac pump and the other to a mercury manometer. When the pump was started, a partial vacuum was created in the box, and the paper panel pulled inwards. However, the paper did not break because the paper was not air tight, and air rushed through the holes. The pump was not able to burst the paper.

When a pressure pump was put on the box, the paper bowed outwards, but again the leakage of air was serious, and the readings were not considered reliable.

A third possibility was tried and found to be successful. The paper panel was made the bottom of a box into which mercury was introduced. The head of mercury was measured, and that head which caused rupture was noted. The mercury did not leak through the holes in the paper; they were much too fine.

The curvature of the paper panel was very small, and the bowing was one to two millimetres. The slight difference of head between the centre of the panel and the edges was considered unimportant. The head was measured to the centre of the panel.

The head of mercury to cause failure in three separate tests were as follows:-

Panel 1	2.05 mm. Hg
Panel 2	1.85 "
Panel 3	2.00 "
Average	1.97.

p.s.i. at R = 12000 ft.

Glass Panels in Mail Chute: Hiroshima

A reasonably good estimate of the peak pressure 600 ft. from X in Hiroshima may be obtained from the cracking and breakage of some glass panels in a mail chute. This chute went from the top floor to the ground floor in the large bank building SE of X, on the SW corner of the T junction of the street car lines. There were three panels on each floor, all below the posting orifice. The panels were 2'6", 1'0" and 1'0" respectively in this order descending. The distance between the supporting steel edges on either side was 6". All the edges were inset into a metal sheet slot, 3/4" deep, but the support against the large force of fracture could only be considered simple. Four of the ~~side~~ mid panels on the ground and first floors were fractured. One of the two that escaped was a 2'6" panel. All but one of the panels on the higher floors were intact. It appears that the peak pressure near the ground was greater than it was higher up. No doubt the panels in the upper floors escaped fracture to some extent because by the time the reflected shock from the ground reached them, some air had entered the posting orifice and built up a supporting pressure of a few p.s.i. on the inside. No doubt also, the peak pressure does drop in the conditions prevailing here at the rate of perhaps 1 p.s.i. per 20 ft. rise above ground level. This point needs theoretical study.

Specimens of the glass were submitted to Mr. H. Moore, the glass technologist of Messrs. Pilkington Ltd. He stated that the tensile yield strength against bending fracture of the glass would be very close to 9000 lb/in.^{2} He also expressed the opinion that glass was made by the American Plate Glass Company in America! The thickness of the glass was 0.23".

Considering the panel as a beam (at 6" simple supports,) we have that the bending moment causing fracture was 4.5P lb. in. This equals 9000 x $(.23)^2$ /6 lb. in. Hence P = 17.5 p.s.i. Correcting for the finite length of the panel requires the addition of 25% to this value of P. Therefore, we estimate P = 22 p.s.i. This is considered a fair estimate. Perhaps 2 or 3 p.s.i. should be added to allow for the supports being slightly better than simple, and to allow for the fact that the load was not exactly critical. However, it seems safe to say that the peak pressure at the ground level was between 20 and 30 p.s.i., and that the best estimate is

P = 25 p.s.i. at R = 600 ft.

The pressure was, therefore, 0.96 p.s.i. for the half scale panel. Allowing for the fact that on the full scale, the paper would be relatively one half the thickness, we get

$$P = 0.48 \text{ p.s.i. at } R = 12000 \text{ ft.}$$

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$$P = 25 \text{ p.s.i. at } R = 600 \text{ ft.}$$

Wooden floor in Hiroshima

The telephone exchange in Hiroshima 3800 ft. W.N.W. of X had a small wooden floor as a superstructure on part of the main ground floor, which was of concrete. The wooden floor was covered by mats at the time of the explosion and the pressure of the blast wave was sufficient to break the joists of one of the two weakest panels, namely the end ones. The broken panel is shown in picture H90; that part of the floor board lying loose was broken by us. The whole panel was taken to pieces in order to get the details of the construction and suitable pieces for test.

The strength of the panel which broke was entirely that of the joists; the floor boards gave no resistance to the downward thrust of the pressure. The boards were tongued as shown in Figure 8 and the space below the floor was to a high degree of approximation air tight to the blast.

It is interesting to note that the panel corresponding to the one that broke, at the other end of the floor, did not fail. Hence, we may have some confidence that the peak pressure acting on the floor was very little in excess of that sufficient to cause failure of the end panels.

The panel which gave way was 43" x 136". It was supported by 9 equidistant joints, at 17" centres. The ends of the joists nearest to the wall rested on the brick party wall, and were, therefore, only simply supported. The joists ran from the party wall over a beam 4" x 6" and then over two more similar beams each spaced at 43" centres, and finally on to a small brick wall, based on the conrete floor.

Eight of the nine joists under the panel were snapped. The one that did not fail was the corner one. The one at the other corner was different from the rest; it was simply supported at both ends. Apparently that corner of the floor had been taken up at some time and the joist cut through or replaced by a short piece.

The wood was all in very good condition - there was not the slightest trace of damp. A piece of one of the broken joists, with parts of the floor boards still attached, was brought back for tests. The tests were made by the Forest Products Laboratory, Princes Risborough.

The dimensions of the joists were taken, and the distance of the break taken from the simply supported end. The exact point of break could not, of course, be located; we simply measured to a point which appeared to be central.

Beginning with the joist which was simply supported each end, we found

Joist number	Depth (inches)	Width (inches)	Point of break (inches)
1	$2\ ^1/_{16}$	2	22
2	2	2	14
3	$2\ ^1/_{16}$	$2\frac{1}{8}$	16
4	$2\ ^1/_{16}$	$2\ ^1/_{16}$	15
5	$2\ ^1/_{16}$	2	14
6	$2\ ^3/_{16}$	$2\ ^1/_{16}$	12
7	$2\ ^1/_{16}$	2	14
8	$2\ ^1/_{16}$	2	14
9	$2\frac{1}{8}$	$2\ ^1/_{16}$	not broken

Hence, the average dimensions were $2\ ^1/_{16}$" x $2\ ^1/_{16}$", and the point of break was 14" from the simply supported end, except for the end joist which was simply supported both ends and broke in the middle.

To represent joists 1 - 8 we consider a beam on three supports all at the same level, the separation between the beams being L (L = 43"). The left-hand support and the central support are simple while the right-hand one is clamped horizontally. Let w be the load per inch run, and measure x from the left-hand support. Writing y for the deflection, we have the following conditions:-

$x = 0$ $y = 0$ $y'' = 0$

$x = L$ $y = 0$ y' continuous y'' continuous

$x = 2L$ $y = 0$ $y' = 0$

Solving this beam problem, we find that the maximum bending moment occurs at $11L/28$ from the left-hand end, and has the value $0.0774\, w L^2$. Hence the break should occur at 17" from the free end, compared with the observed value 14".

To estimate the peak pressure, we have that 7 of the nine joists were of the category just considered. One other (joist number 3) had a knot at the break, and we assume two-thirds full strength for this joist. The joist simply supported at both ends has a maximum bending moment at the centre of $0.125\ w\ L^2$. Hence this joist is only 0.62 as strong as the others.

Let P be the maximum hydrostatic pressure. Then the load per inch run on the 9 joists is 136P. Equating this to (7 + 0.67 + 0.62) the strength of the beam problem above, we get as the load for the single joist

$$w = 136\ P/\ 8.28$$

According to the Forest Products Laboratory, the maximum bending moment for a section 2" x 2" is the average of 14050 and 17280, i.e. 15660 lb.in., less 10 per cent. for the fact that the wood was cross-grained 1 in 10 at the failure. Therefore, the bending moment to snap a 2" x 2" section is 14100 lb.in. The corresponding figure for a section 2 1/16" x 2 1/16" is 15500 lb. in. Hence.

$$0.0774\ (136\ P/\ 8.29) \times 43^2 = 15500$$

$$p = 6.6 \text{ p.s.i.}$$

There still remains open the question whether the failure of the joists was progressive, and, of course, the time taken for failure. It does not seem profitable to elaborate the calculations further; since some of the corrections are positive and others negative, we have as our best estimate

$$P = 6.6 \text{ p.s.i. at } R = 3800 \text{ ft.}$$

It should be noted that there were two other wooden panels, supported by joists in another part of the main floor. The joists spanned 34", were simply supported at both ends, and spaced at 17" centres. The dimentions were $1\frac{1}{2}$" horizontally by 2" vertically. The joists had failed badly. The critical peak pressure is between 5 and 6 p.s.i., but these panels were not considered as good for our purposes as the one described above.

Toolchest, Nagasaki

An excellent example of the dishing of a metal plate was found in a heavy machine shop 2300 ft. from X. The plate was 16" x 18" and there was a permanent set of $\frac{3}{4}$" at the centre. No distortion of the supporting edges could be observed even when a straight edge was held against them.

A piece of the plate was brought back for measurement; the thickness was 0.056".

A model to the scale of 3/7 was made and a load was applied to the plate by a testing machine pressing through some wooden boards on to some wet sand lying on the plate.

~~Diagram shows the arrangements.~~ Four tests were made and the results are shown in the table below, and graphically in Figure .

Thickness of metal plate .021", Surface dimensions $6 \times 6\frac{3}{4}$" (scale 3/7)

Internal dimensions of box $6\frac{7}{8} \times 7\frac{3}{4}$"

Load	Deflection (1)	Deflection (2)	Deflection (3)	Deflection (4)
15	0	0	0	0
215	0.07	0.08	0.07	
415	0.09	0.10	0.09	
615	0.12	0.13	0.11	
815	0.14	0.15	0.15	
1015	0.18	0.18	0.17	
1215	0.20	0.20		
1415	0.23	0.23		
1615	0.27	0.27		
1815	0.29	0.29		
2015	0.33	0.32		
2215	0.37	0.48		
2415	0.45			0.41
Permanent set	0.35	0.40	0.03	0.30

Load in pounds; deflections in inches; permanent set in inches after loading to maximum value given in the column.

Second test gave a sudden collapse at 2200 lb.

By interpolation, for a set of 9/32", W = 2035 lb. to which must be added 15 lb. for sand.

Hence L = 2050 lb.

P = 2050 ÷ 6.88 x 7.75

= 38.5 p.s.i.

Of the four tests (1) and (4) were the best, and gave the most symmetrical dishing. Taking only the two, we get 40 p.s.i. as the peak pressure. This ~~is~~ result our ~~best~~ estimate at present, but the writer, for reasons given in the next section, is sure that the true figure is rather less, probably 35 psi. The value taken provisionally is 35, and can be checked by better experimentation later ~~Hence~~

P = 35 p.s.i. at R = 2300 ft.

Safe door, Hiroshima

A safe of old and cheap design 200 ft. from X was dished by the blast. The two mild-steel doors, symmetrical about their central free edges were 72.4" x 24.7". The thickness was 0.363". The set at the centre of the free edges was 4". The two short sides of each door were simply supported, the long central edge was, of course, free and the outside long edge was simply supported except for two hinges each 10" long, the centres of the hinges being separated by 20". A model was made of half the door and an approximately uniform load was applied by means of a testing machine acting through wooden blocks and wet sand. ~~Diagram gives the arrangement.~~ The results of the test and the deductions therefrom are given below.

Door model 14.8 x 4.95". Inside dimensions of box 6 x 15.7". Not an exact model. Length and width to scale 1/5. Thickness on one-fifth scale would be 0.0726". Actual thickness 0.056".

Load (lb.)	Deflection (inches)
0	0
25	0.20
100	0.25
200	0.30
300	0.35
400	0.39
500	0.42
600	0.47
700	0.54
800	0.58
900	0.61
1000	0.62
1100	0.65
1200	0.68
1300	0.70
1400	0.72
1500	0.74
1600	0.76
1700	0.79
1800	0.84
1900	0.90
2000	0.95
2100	1.02

Permanent set after remaining 2100 lb. load was 0.23".

Similar experiment. Same arrangement, but thickness of metal plate 0.021".

Load (W lb.)	Deflection (d ins.)	7.1W	0.375d
5	0	36	0
10	0.13	71	0.049
15	0.21	107	0.08
20	0.27	142	0.10
25	0.32	178	0.12
30	0.41	213	0.15
35	0.47	249	0.18
49	0.62	348	0.23
63	0.78	447	0.29
77	0.87	547	0.33
91	0.95	644	0.36
105	1.07	743	0.40
119	1.22	843	0.46
140	1.55	992	0.58
154	1.70	1090	0.64
168	1.95	1190	0.73
178	2.15	1260	0.81

Did not give a very well shaped permanent set. The free edge was not bowed very regularly but the set was approximately 0.5".

It will be seen by a comparison of the last two columns, with the previous table that the ordinary laws of flexural elastic deformation hold fairly well. According to these laws, if the thickness is increased n times, and the load n^2, then the deflection is n times less. Figure 5 shows the results graphically.

From Figure 5, the load required to produce the scale deflection 0.62" is 2700 lb.. Scaling this back to a thickness 0.0726", we get the load as 4600 lb.. The pressure is therefore

$$P = 4600 \div 6 \times 15.7$$
$$= 49 \text{ p.s.i.}$$

This figure perhaps needs correction to allow for the fact that the mild steel of the door in Hiroshim had a different yield strength than the rolled steel plate on which the test was made. The correction is probably only a few percent. and will be neglected. We therefore have

$$p = 50 \text{ p.s.i. at } R = 0 \text{ ft.}$$

This result is not considered entirely ~~trustworthy~~; an improved experime should be made, and will probably show that P was between 30 and 40 p.s.i. INSERT FROM OVER

Dished office cabinet in Hiroshima

An office cabinet in the Communications Bureau in Hiroshima 5000 ft. E.N.E. of X was dished by the blast. The top metal plate was 23$\frac{5}{8}$" x 15", and the thick thickness was 0.018". The edges were crimped $\frac{3}{4}$" over the sides. The set at the centre was 1.3", and the two long edges were bent in $\frac{1}{4}$" and 3/16" respectively. The short edges were straight.

It was considered that the tests on the Nagasaki tool chest provided sufficient data for evaluating this observation. According to the tests on the tool chest, a load 41 p.s.i. on a panel freely supported at the edges, 0.021" thick and 6" x 6$\frac{3}{4}$" sides gave a set 0.35". This is just the amount required according to the scaling method used below.

We define the effective size of the plates in terms of the sum of the inverse squares of the sides. This method of procedure is reasonable as long as the two edges are not widely different in length. If the edges were very different, the whole problem would change in character. For example, if one edge were infinite, the metal plate would yield much more easily; only a bending set however would be involved, and not a stretching of the central parts of the dish. A bending set can easily be straightened out with a mallett and anvil, but the sets of the type we are considering cannot, because the central parts of the metal have been stretched.

Thus for the office cabinet

$$L_1 = 2/\left[1/(15)^2 + 1/(23.6)^2\right]^{\frac{1}{2}} = 17.9"$$

and for the plate representing the tool chest

$$L_1 = 2/\left[1/(6)^2 + 1/(6.75)^2\right]^{\frac{1}{2}} = 6.25"$$

The ratio of metal thickness to L for the office cabinet is 0.00101 and for the model tool chest is 0.00336. The pressures are in the squares of these ratios.

INSERT

There is a possibility that frictional forces in the sand allowed some of the load to be supported by arching arching in the wet sand, based on the edge supports. An air balloon would be a more satisfactory way of applying a uniform pressure, whose magnitude was known exactly. However, time did not permit a better technique being developed; an attempt will be made at leisure to check the ~~[illegible]~~ guesses made in this section and the previous one, although it is confidently expected that the results will not be much in error.

Hence

$$P = 3.7 \text{ p.s.i. at } R = 5000 \text{ ft.}$$

Failure of a wooden wall 15000 ft., Hiroshima

This observation is considered fairly reliable. The discordance between the pressure estimated here, and that estimated at 12,000 ft. from the paper panels is probably real, and illustrates the local variations in the peak pressure at large distances.

One panel of the end wall of a large timber storage barn 15,000 ft. S.E. of X in Hiroshima had failed under the blast. The barn was practially airtight; there were no windows and only two small doors, both of which the owner of the barn stated emphatically were closed at the time of the explosion. There were cracks about 1/16" between the planks of which the wall was made. The particular panel which had failed was made of vertical planks 0.65" thick nailed on to seven horizontal pieces of wood 1.4" horizontally x 1.85" depth (average values). The point of failure averaged 51" from one end. The planks were about 11" wide and 12' high. The wood was red pine similar to the wood of the joists of the telephone exchange. The clearance at the bottom, above ground, was 1", and the planks were free top and bottom. The cross pieces, of which there were 7, each 110" long, were nailed at each end to sturdy circular upright pieces, buried in the ground. The end wall consisted of two panels of the type described, and the side walls were similar, except that the spans were about 85", instead of 110". The inverted V spaces at the two end walls were filled in by planks, mounted horizontally. These were undisturbed, as were all panels except the one described. Using the measured yield strength of the timber, the hydrostatic pressure is 0.23 p.s.i.. This, we estimate, must be increased to 0.28 p.s.i. to give the peak pressure in the blast. Therefore

$$P = 0.28 \text{ p.s.i. at } R = 15000 \text{ ft.}$$

~~Wooden Wall, Nagasaki~~

Kamigo Barracks Nagasaki

The Kamigo Barracks were not all complete, but most of the buildings were occupied by workers from the Mitsubishi works. The buildings were merely flimsy sheds. An approximate value of the peak pressure was obtained by noting that two of the sheds which had collapsed came down because the upright posts supporting the wooden plank walls, and the roof, had snapped in the middle. The shed folded in like a ~~concertena~~. concertina

The members that snapped were 4" x 3", simply supported top and bottom, of height 10 feet. They were spaced 8 feet apart. The wood was pine.

The load per square inch on the wall that would cause the snapping of the vertical supports is 0.40 p.s.i. The correction to be made for the finite yield time is not significant.

Near to the barracks were some paper panel screens exposed "side-on" to the blast. These were not damaged although they would have failed at 0.5 p.s.i. Hence we may say with moderate accuracy that.

$$P = 0.45 \text{ p.s.i. at } R = 23{,}000 \text{ ft.}$$

SECRET

Reinforced Concrete Panel Hiroshima.

The basement of the Chamber of Commerce, Hiroshima, 1,000 ft W. of X, was used as an air raid shelter. The ground sloped a little, away from the main road, and the back side of the building was a few feet lower than the front. Three panels of the back of the building (i.e. N side) in the basement, freely exposed to the outside air, ~~and~~ were dished in by the hydrostatic pressure. The dishing was severe, and it was clear that the steel reinforcements had stretched until the panel was in equilibrium with the pressure difference on the two sides. The concrete was cracked, but very little had actually fallen off the reinforcements. A reasonable estimate of the peak pressure may be obtained by applying the usual theory of the dishing of a membrane by pressure.

The panel was 8' x 13', and the dish was 22". The concrete was $4\frac{1}{2}$" thick, but this fact is not required, since the concrete acted only as a medium for applying the load to the steel. The reinforcements were 5/16" rods on 6" centres.

According to the theory of dishing given by Taylor, and a similar theory by Kirkwood (see report S.W. 24 equation 44), the dishing H produced by a pressure P, the sides being 2a and 2b, $(a > b)$ is given by

$$H = \frac{P}{T} \left(\frac{16b^2}{\pi^2}\right)\left[\operatorname{sech}\left(\frac{\pi a}{2b}\right) - \frac{1}{27}\operatorname{sech}\left(\frac{3\pi a}{2b}\right) + \cdots\right] \qquad (21)$$

where T is the yielding tension per inch run.

In our case assuming a 20 ton steel, T = 520 lb/in. Substituting into the ~~close~~ formula (21), it is found that P = 20 p.s.i. The accelerations of the panel were large, and no ~~and 3 p.s.i. seems a reasonable~~ correction for the finite time of ~~yield.~~ need be made, in view of the fact that the steel had stretched and become slightly thinner, and probably ~~weaker~~. therefore could take less tension.

P = 20 p.s.i. at R = 1000 ft.

SECRET

Failure of Reinforced Concrete Panels Nagasaki and Hiroshima.

The ground floor of the Administration Building of the Torpedo Works in Nagasaki 4,050 ft. N. of X acted as the roof of the air raid shelter in the basement. The shelter was practically unventilated; the windows, which in any case were small, had been almost entirely bricked up. The only opening of any size was the door at the top of the stairs connecting the ground floor to the basement. The basement was about 100' x 30' x 9'. Thus, when the pressure of the explosion wave reached the building, the pressure in the shelter did not change. On the other hand, the large window space on the ground floor level allowed the pressure inside to reach that of the outside almost instantaneously. The effect of the pressure difference on the two sides of the reinforced concrete floor was to dish in most of the panels. A careful study was made of the construction of the floor in order to estimate the peak pressure in the blast.

Practically the same situation to that just described was found in the Radio Building in Hiroshima 3100 ft N.E of X Again, details were taken of the floor construction.

The problem of the Nagasaki panel was put to the Cancrete Section of the Road Research Laboratory, Harmondsworth, to estimate the uniform static load that would cause failure to the extent observed. It seems, however, that not sufficient is known about concrete panels to make any absolute figures certain. The edge conditions of the panel are important for assessing the load, and all that the Road Research Laboratory could say, after considering the problem in some detail, was that the load was more than 10 p.s.i. and less than 20 p.s.i.

Much closer limits to the peak pressure may be had by comparing the floor in Nagasaki with the one in Hiroshima. Since the pressure acting on the latter is known with some accuracy from other observations, it is possible to obtain from the comparison a reliable estimate for Nagasaki.

The Road Research Laboratory considered that the exact amount of dish was not significant; the panels gave their maximum resistance before they first failed; once failure of the steel was caused, the panel yielded more easily. The concrete in the two floors were very similar, both described from samples, as of moderate quality, and the thickness in each case was 5.8" with a ¾" layer of plaster and asphalt on top.

There were three similar panels in Nagasaki, each 15' x 23' (see Pictures N.51). The panels were continuous on their 23' sides, running over heavy beams. The 15' sides were attached on one side to the walls of the building, and on the other ran over a heavy beam and then on to the other wall. The details of the reinforcement were obtained by knocking a hole 4' x4' in the floor. The reinforcements were all ½" rods, disposed as shown in Figure . The reinforcements were brought up over the supports, and overlapped the next panel by about 3 feet. The deflection at the centres were 9.5", 9.8" and about 4". (The third panel could not be measured accurately because an enormous pile of rubble had been thrown on it). A fourth panel with a little extra support in one corner, due to the stairs, had not dished.

The floor panel in Hiroshima was 20' x 20'; the rods were ½" at 6" centres A second similar panel had not failed. The panel was not supported as well as the one in Hiroshima. Two contiguous edges were fixed to the outside walls; one of the other edges was continuous, over a heavy beam underneath and then on to the far wall. The fourth edge was also continuous to a neighbouring room, but the support was a vertical wall, across the building. On the other side of this wall was a similar panel which had not failed. The wall did not run through to the basement. There appeared to be no failure of this wall, but a curious pattern was seen on the wall itself. Vertical gashes about 3" wide and 10" centres showed clearly in the mortar. No doubt the steel reinforcements stretched and the stress distribution had the periodicity of the steel,. and caused the plaster to crack and fall away near the steel. The steel was exposed in a few places.

The floor was also attached to a second vertical wall, which did not go through to the basement. This wass was 5' 6" from one side and made the fourth wall of a room 20' x 14' 6". This wall contained a door and a window. On the other side of the wall was the passage leading from the fron door. The passage wall had parted from the floor; there was a 3" gap at the centre, and the steel reinforcements were necked and all but the end ones snapped.

The deflection at the centre of the dish was 10" and the centre of t he dish was central in the 20' x 14' 6" room.

It is clear how the Hiroshima floor behaved.. As the pressure came on, the 14' 6" x 20' panel failed; then the passage wall failed, and the 20' x 20' panel gave a few more inches.

Summarising what h[illegible] been said above, we have that [illegible]he Nagasaki panels 15' x 23' dished 9.8" and the Hiroshima panel 14' 6" x 20' dished 7". Since the exact amount of the pressure wave and the build-up of pressure below the panel, we may obtain the ratio of the peak pressures in the two cases simply by comparing their structures. Many methods have been tried, but none appears more satisfactory than simply taking the ratio of the amounts of steel per square foot. The ratio Nagasaki: Hiroshima is 5; 4

Since the peak pressure in the wave was 10 p.s.i. on the Hiroshima panel, the pressure was 12.5 p.si. on the Nagasaki panel. This estimate is probably accurate within 1 p.s.i.

P = 12.5 p.s.i. R = 4,050 ft. in Nagasaki.

(38)

Earthenware drain pipe in Nagasaki

This is an interesting example, because it demonstrates the great pressure developed on the ground in Nagasaki. Unfortunately, the observation does not permit more than rough accuracy.

A vertical earthenware drain pipe, half embedded on the sloping bank of the approach to the Shiroyama Primary School (a few yards from the place where picture N was taken) 1150 ft. W. of X, broke under the pressure of the blast. The embedded part was very firmly supported, and the whole pipe was held in position by a layer of mortar ¾" thick. The pipe was only 30" long; the external diameter of the earthenware was 10" and the thickness ½". The entire exposed half was broken to pieces; most of the pieces were swept away by the blast, but a few were trapped inside. There seemed no doubt that the pipe had failed by crushing and not by flexure.

Professor A.J.S. Pippard, of Imperial College London, kindly made a test described in his letter which is printed below. Using his data, neglecting the strength of the mortar, and scaling down from a thickness ⅞" to ½", the crushing pressure was 150 p.s.i.

$$P = 150 \text{ p.s.i. at } R = 1150 \text{ ft.}$$

This estimate must be qualified to some extent, as follows. It is not clear how the estimate of peak pressure should be modified to allow for the contours of the bank and thus obtain an estimate for level ground. The pulse that broke the pipe was probably the reflected wave from the path just in front of the drain pipe. The peak pressure, of course, is multiplied by a factor at least four on this reflection. When this reflected pulse strikes the bank, still a further multiplication is introduced. In other words, the incident downward pulse has been funneled into a wedge shaped region of angle about 120°, one side of the wedge being the path, and the other the bank. The multiplication produced in this way may have been as high as 10 over the "free air" pressure.

Making allowances for the unavoidable uncertainties in the cause of fracture of the pipe, it still seems reasonably safe to say that the peak hydrostatic pressure on level ground 1150 ft. from X would be of the order 100 p.s.i.

Dear Penney,

I have now made the test on the earthenware pipe which I think is as near as we can hope to get to the conditions you described to me.

The pipe was 10¾" outside diameter and 9" inside diameter and a section approximately 4" wide was cut from this and bedded in sand in a specially made box. Care was taken to prevent the sand from getting inside the pipe by puttying the edges of the specimen to the sides of the box. A stiff bar was placed on the top surface of the sand and a load applied to its centre; thus approximating to a uniformly distributed load along the sand resting on the top section of the specimen.

The test went quite steadily until a load of 4.75 tons was reached when a crack was heard and on dismantling the test we found that the specimen had cracked into four equal quadrants, the cracks being at the ends of the diameters through the load and at the ends of the diameter at right-angles to this. It looks, therefore, as though this pipe would take from 1 - 1¼ tons per inch length before failure occurred, provided the load can be considered reasonably uniform as seems likely in your case.

Yours sincerely,

(sgd.) A.J.S. Pippard

(40)

DRAG PROBLEMS

Telegraph pole, Nagasaki

Telegraph poles were, on the whole, disappointing. Several were still standing immediately under the explosion; those from a few hundred feet up to 3500 feet were all down. At 3500 feet, an occasional pole was standing, and at 4500 feet most were standing. The difficulty in interpreting the failure of a pole is, of course, the uncertain pull from the wires. The most favourable cases were poles in a line running to the Mitsubishi Torpedo Works. One pole, a little off the main line, presumably carrying a side line, at 3400 feet from X was measured; the wood was in good condition, there appeared to be only one cross bar, and the blast ran in the direction of the wires. The pole was snapped at ground level.

Diameter at base 8". Diameter at top 7". Height 27'

Wood Thuyopsis dolobrata or Conninghamia lanceolata

Bending Moment to snap 8" section, according to Forest Products Laboratory, Princes Risborough, 1,125,000 lb.in.. The drag pressure was 3.24 p.s.i. Assuming a drag coefficient 0.5, apparently the proper value for a smooth cylinder of such large diameter, a peak pressure was 16 p.s.i.

Now we have to consider two factors, influencing our opinion in opposite directions. First, that the pole snapped, so that the estimate must be increased. Second, that the pole carried wires. Since the wires were not much affected by the wind of the explosion, it is submitted that a peak pressure 16 p.s.i. at 3400 ft. is approximately correct.

$$P = 16 \text{ p.s.i. at } R \simeq 3400 \text{ ft.}$$

An interesting observation, but not one from which we have attempted a qualitative estimate, related to a pole near the Shiroyama Primary School. This pole snapped 11 feet from the top: the diameter was uniformly 7", and the surface was very smooth. The distance from X was 1100 feet. Apparently this pole snapped in the incident pulse, before the reflected shock reached it. Other examples in the range 1000 ft - 1500 ft. were found where the rather heavy and complicated tops of power poles snapped the pole near the top. (See picture N 84).

Whether the tops came off because the poles were guyed just below the tops, or whether the tops received the impact of the initial downward shock and immediately snapped off, was not clear. Probably both effects were present simultaneously.

It is worth noting that practically all of the poles that came down snapped; none of them merely turned in the ground, displacing the earth. A few came out bodily, leaving a hole about five feet deep. Perhaps the prevalence of typhoons in Japan was the reason for the very strong method of fixing the base of the pole.

Failure of I beam, Hiroshima

A rolled mild steel I beam 1900 ft. W. of X in Hiroshima failed under the wind pressure. The beam was vertical, and was 26 ft. high; it was used to carry a cross wire across the road to a similar beam on the other side. The cross wire carried the power line for the street car. There appeared to be no need to allow for the drag of the wire on the beam, and there were no complications involved in the nature of cross arms or other objects at the top of the beam. The blast was parallel to the centre web. Figure 7 gives a tracing of the shape of the beam, copied from a piece of paper pressed against the end of the beam. (There was one other similar beam which had collapsed completely). The beam which stood up was partly shielded from the blast by a building, and therefore the estimate based on this beam must be considered as a lower limit.

Let S be the drag pressure per square inch on the beam. Then the bending moment about the base is 242000 S lb. in.

Let Y be the yield strength. Then the yielding bending moment is 16.9 Y, and with $Y = 25$ tons/in^2., the most probable value for this steel, the bending moment is 95000 lb. in. Hence

$$S = 2.56 \text{ p.s.i.}$$

The drag coefficient is about 0.8, and the peak pressure in the shock just sufficient to cause failure is 12 p.s.i.

Allowing for the fact that one I beam was prostrate, while the partly shielded one was only slightly bent, we estimate that the peak pressure was about 15 p.s.i. Thus $P = 15$ p.s.i. at $R = 1900$ ft.

Flagpoles in Hiroshima.

Two observations on flagpoles in Hiroshima now to be described are regarded as giving estimates of high accuracy. The Engineering and Aerodynamics departments of the National Physical Laboratory (Teddington) made tests on a length of one of the poles, including the bent part, and estimated the ~~minimum~~ shock pressure that would just cause yield. Their results are described in the letter, printed below. Correction must be made to allow for the inertia of the poles and the finite angle of bend.

The first flagpole, from the ~~bank~~ (roof of the) building 3,200 ft. E. of X, was of length 239", ← 239"
outside diameter 2.40", thickness 0.140", and yielded an angle 0.114 radians. According to N.P.L. the drag pressure was 0.50 p.s.i. and the shock velocity to cause yield was 1.186 c where c is the sound velocity in the original air. The drag coefficient was 0.45. The shock pressure was 7.0 p.s.i.

The moment of inertia is 8850 lb ft^2, and the yielding bending moment in the "set" condition was 9.2 x 10^4 poundals ft.
Using formulae (9) and (14), and knowing by the method of trial and error that the final shock pressure is about 10 p.s.i., we have

α = 2.44 sec^{-1}. We ~~find~~ then obtain

$$F_o = 0.923 \text{ p.s.i.}$$

Finding a self-consistent solution, using the variation of drag coefficient with Reynolds number given in the N.P.L. diagram (Figure 11 of this Report), we get that the drag coefficient was 0.52, the time of yield was 0.28 sec. and

$$P = 9.2 \text{ p.s.i. at } R = 3{,}200 \text{ feet.}$$

The error in this estimate is considered to be less than 10%.

The second pole on the Electric Company Building distance 2,100 ft from X ~~[illegible]~~ was of length 114" outside diameter 2.40" thickness 0.140" and yielded an angle 0.075 radians. According to N.P.L. the shock velocity was 1.342 c, and the peak shock pressure was 13.6 p.s.i. The drag pressure to cause yield was 2.62 p.s.i. and the drage coefficient was 0.655. The moment of inertia was 960 lb ft^2, and the yielding bending moment as before was 9.2 x 10^4 poundals feet.

Using the value of α = 3.1 sec^{-1}, we find that in order to account for the observed yield, the peak drag pressure was 3.44 p.s.i. The time of yield was 0.11 seconds, and the drag coefficient was 0.69. The peak pressure was 15.4 p.s.i.

P = 15.4 psi at R = 2100 ft.

Copy of letter from Dr. Hankins N.P.L. to Dr. Penney.

Dear Dr. Penney,

Further to your visit of 23rd November the calculations suggested have now been completed.

The tube left with us was measured and appeared to be straight down to a point about 18 inches from the lower end. A portion 18 inches long was cut to include the straight portion and tested in bending using four point loading in a testing machine. The bending moment applied when the strain-movement curve ceased to be linear (as determined by electric strain gauges) was taken as being equal to that applied at the point of junction of the distorted and undistorted parts of the tube during the explosion. From this the uniformly distributed pressure which might have been applied to the tube was calculated using conventional formulae.

Results are as follows:-

Length of Mast - 239 inches

Effective Pressure = 0.5 ±. 012 lb./sq.in.

Length of Mast - 114 inches

Effective Pressure = 2.62 ±. 18 lb./sq. in.

In calculating the strength of the blast waves necessary to produce these pressures the simplifying assumption has been made that the wave is of the form of a normal shock wave travelling perpendicularly to the mast and the effect of heat radiated from the explosion has been neglected. It should be pointed out that while the pressure differences associated with the wave front may be considerable the time taken for the wave to pass the mast (less than 0.2 millisecs) is small compared with the natural period of the mast (about ½ sec. for the 20 ft. mast). It is therefore assumed that permanent set is caused by the pressures developed by the air stream following the wave.

The drag coefficient for the mast has been taken as that corresponding to a fairly smooth cylinder the results for which are available from N.P.L. Compressed Air Tunnel tests (see Fig. 1). Over the range of Reynolds Number (R) concerned the drag depends considerably on the roughness of the surface (e.g. for a polished metal surface at $R = 5 \times 10^5$ the drag coefficient is 0.35 while the roughest cylinder tested had a drag coefficient of 0.79). The values given are a fair estimate considering the nature of the surface of the mast. With these values of drag coefficient and for the atmospheric conditions specified below, the velocity of the wave passing over the mast to give the calculated pressures is about 1350 ft./sec. for the 20 ft. mast and 1530 ft./sec. for the $9\frac{1}{2}$ ft. mast. The conditions behind the waves may be read off from Fig. 1. It will be noticed that for the short mast the air following the wave is moving at a Mach number of about 0.45; recent work in the N.P.L. High Speed Tunnels on cylinders indicates that compressibility effects at low Reynolds numbers (in general below critical Reynolds Number) increase the drag coefficient at Mach numbers above 0.3.

Further information on this subject is given in a paper by A. Ferri - The Influence of Reynolds Number at high Mach Numbers (Atti di Guidonia No. 67/69) which indicates that as the Mach number is increased the Critical Reynolds number for cylinders is also increased. By extrapolating the curves given in this paper it appears that at a Reynolds Number of about 8×10^5 the drag coefficient is about 0.9. With this value of the drag coefficient for the shorter mast the wave velocity is about 1470 ft. per sec.

The figures on which the curves of Fig. 1 are based are given on the accompanying sheet.

Yours faithfully

G.A. Hankins.

NATIONAL PHYSICAL LABORATORY

Engineering Division

Basis of Calculation

The atmospheric conditions have been taken as Pressure (p_1) 14.67 lbs/sq.in.; Temperature (T_1) 25°C; Density (ρ_1) .0739 lbs./cu.ft.

(The air has been assumed dry, the influence of humidity is unlikely to cause more than a ~~few~~ one per cent. error)

The velocity of sound at 25°C. (a_1) - 1138 ft./sec.

Viscosity of air at T_3°A given by

$$\mu_T = \mu_{273} \left(\frac{273 + C}{T_3 + C}\right) \left(\frac{T_3}{273}\right)^{3/2}$$

where μ_{273} = 1.153×10^{-5} lb./ft./sec.

$C = 117$

Reynolds Number $R = \dfrac{u_3 D \rho_3}{\mu_3}$

Where u_3, ρ_3, T_3, μ_3 are velocity, density, temperature and viscosity of air behind the wave.

D. is diameter of mast. (0.2 ft.)

Drag coefficient C_D = Pressure on mast $/ \frac{1}{2} \rho_3 u_3^2$

Mach Number of wave (M_1) = U/a_1 where U = velocity of wave.

Mach Number of air behind wave (M_3) = U_3/a_3

where a_3 = velocity of sound behind wave $(1138\sqrt{\frac{T_3}{298}}$ ft./sec.)

The conditions behind the wave given in Fig. 1 have been calculated assuming the well known Rankine-Rayleigh relations through a perpendicular shock wave.

The "stagnation" temperature rise plotted is the excess temperature over the ambient temperature (T_1) assuming that the air behind the wave is brought to rest adiabatically.

The energy dissipation has been calculated from the expression

Energy dissipation per sq. ft. of wave per sec. = $\rho_3 \underline{\{u_3\, C_p(T_o^1 - T_1)}$ move up a little

where T_o^1 = Stagnation temperature rise.

C_p = Specific heat of air at constant pressure (taken as 0.2413 C.H.U/lb./°C.).

SECRET

Wrought iron ladders on the roof of City Offices, Hiroshima

Three similar wrought iron ladders on the roof of the City Offices in Hiroshima 3600 ft. S.S.E. of X were affected by the wind of the explosion. The roof was not all at the same height; several parts were 8-10 ft. higher than other parts. The ladders were provided for getting from one region of the roof to another. The ladders went up a wall, some 10 feet high, over a parapet wall and then down about two feet. Pictures H 85 and H 86 illustrate the construction of these ladders. The wind of the explosion happened to be parallel to the parapet, and caused the tops of the ladders to bend over. ~~Diagram gives the relevant dimensions.~~

Suppose that the peak drag pressure was S p.s.i. Then the bending moment of the drag about the point of failure was 4340 S p. s. i.

Now we must estimate the bending moment that caused the failure of the iron. It was not clear to the writer whether the stress distribution across the section was two symmetrical parts, one in tension and the other compression, the magnitude of the stress everywhere being the yield value, or whether the stress was more like that prevailing while the strain was still elastic. The bending moment per unit width in the two cases are $Ta^2/4$ and $Ta^2/6$ where a is the thickness and T is the yield strength. Accordingly a piece of wrought iron was clamped as a cantilever; the loaded free length was 27", the width was 1.45" and the thickness was 0.266". The load deflection results were as follows, beginning with half the weight of the bar plus the weight of the pan.

Load (lb.)	Deflection (ins)
2	0
7	0.65
12	1.34
17	1.97
22	2.60
27	3.27
30	3.80
32	4.8 (creeping)

The load-deflection curve was plotted. The yield load was 30 lb., and the bending moment to cause yield was 800 lb. in.

Scaling this to the ladder problem, the bending moment for yield of both arms was 3470 lb. in.

The drag pressure to cause yield was, therefore, 0.80 p.s.i. The drag coefficient is about 0.8, and the peak pressure was 6.4 p.s.i. Allowing for the inertia of the ladder and the decay of the shock wave, the peak pressure is corrected to 7.5 p.s.i. Hence

$$P = 7.5 \text{ at } R = 3600 \text{ ft.}$$

Shrine in Hiroshima

The appearance of the overturned stones is shown by (pictures H82, H83). This particular shrine was 3800 ft E of X. There were two types of stones, both artificial granites.

(1) Number I granite, with bold markings and very highly polished surface. Density 2.57 gm. per cc.

(2) Number II granite, dull grey stone, rough surface. Density 2.38.

Measurements were usually confined to I.

The blast was perpendicular to one face. Stones overturned

X = 9.8" Z = 28.5" (five examples almost identical) Granite I
X = 8.1 Z = 29" (two examples) Granite I
X = 6.5 etc

Follow on from next page

$X = 6.5''$, $Z = 17.5''$ (one example; over forward) Granite I.

of these, the second is the most nearly critical, and we have $X^2/Z = 8.55$ cm.

We know that P is approximately 7 p.s.i., and (from Table I,) $\sqrt{\alpha}$ is 2.0 sec^{-1}. Solving (20) for Fo, we find

$$Fo = 0.92 \text{ p.s.i.}$$

Hence the drag coefficient is 0.82. Notice how the inertia of the stone (or what comes to the same thing, the decay of the blast wave) has put up the initial drag pressure. If the wind had been of infinite duration, a value Fo = 0.318 p.s.i. would have overturned the stone, compared with 0.92 p.s.i. actually necessary in this explosion. The time taken to reach the topping position was 0.2 secs.

Shrine in Nagasaki

Many stones were overturned in a shrine 4700 ft. N of X in Nagasaki, near to the Torpedo Works. The blast was not quite normal to the stones, the angle of incidence being about 70°.

The critical stones which overturned were 14x16x38", and the turning edge was the 16" side.

A preliminary solution of the problem shows that P is about 8 p.s.i; we have (from Table I,) $\sqrt{\alpha} = 1.36 \ \mathrm{sec}^{-1}$.

Solving (18)(20) we ~~get~~ find

$$Fo = 1.16 \text{ p.s.i.},$$

compared with a value 0.49 p.s.i. in a steady wind. Using the drag coefficient 0.82 found in Hiroshima, we find that the peak pressure was 7.9p.s.i. (and) the time to reach the toppling position was 0.4 secs.

To correct for the blast not being incident normally, we divide Fo by cos 70°, and have for these stones at normal incidence Fo = 1.21; to find the peak pressure we take the drag coefficient as 0.82 sec^{-1} 70° = 0.77. Hence our final figure is 8.5 p.s.i.

$$P = 8.5 \text{ p.s.i. at } R = 4{,}700 \text{ ft.}$$

Visual Estimates of the Peak Pressure from the Severity of Damage

This section has no claim to scientific accuracy. Nevertheless, notes made at the time of inspection of the damage agree exactly with the results obtained from the analysis described elsewhere in this Report, even though in the writer's preliminary reports, they were considered to disagree.

The writer made a close inspection of the Macdonald Ranch at Trinity. The features of interest were the size of the glass fragments, the damage to window frames and doors, the appearance of cracked plaster, the way in which the roof structure and corrugated iron of the outhouses had been affected, and the general appearance of the building from outside and within.

An attempt was made to estimate where the damage in Nagasaki and in Hiroshima was equal to that in the Macdonald Ranch. The estimates were 12,000 feet S of X in Nagasaki and 7,500 ft. in Hiroshima. In Nagasaki, the damage to the Prefectural Office (10,800 ft) was distinctly more severe then at the Macdonald Ranch, while in the American Consulate (13,000 ft) it was slightly less. In Hiroshima, the damage on the west side of the Mijuki Bashi was distinctly more severe than at the Macdonald Ranch, while 500 ft to S.E. of this bridge, the damage was distinctly less severe.

The peak pressure at the Macdonald Ranch was 1.4 p.s.i. The distance was 10,200 ft. from X. Hence the visual estimates on the damage at the 1.4 p.s.i. level suggest that the tonnage in Nagasaki was 1.48 greater than Trinity, and the tonnage in Hiroshima was 0.40 that of Trinity. The accepted blast tonnage for Trinity is 13,000. Thus, we have from visual estimates alone, the tonnage at Nagasaki was 19,000 , and at Hiroshima was 5,000 .

A further comparison was attempted to assess the distance from X in Hiroshima at which the damage was the same as at Dijima Wharf in Nagasaki (distance 10,500 ft). The place selected was the Gas Works, (distance 6,500 ft.) This comparison gives the tonnage in Nagasaki as 4.2 times that in Hiroshima, again a surprisingly accurate estimate.

Summarising.

P = 1.4 at R = 12,000 ft in Nagasaki

P = 1.4 at R = 6,500 ft in Hiroshima.

SECTION III : THE EQUIVALENT BLAST TONNAGES OF THE TWO EXPLOSIONS

Little need be said in this Report on the difficulty of accurately assessing the equivalent tonnage of an explosion. ~~In the first place, the answer depends on the definition adopted.~~ There are two equally logical definitions

(1) that the blast wave not too near the centre should be fitted to that given by an actual tonnage of T.N.T.

(2) thar the blast wave not too near the centre should be fitted to a theoretical pressure curve obtained by the most complete calculations yet performed.

The disadvantage of (1) is that the question~~s~~ of scaling ~~of~~ small charges to large charges is involved. Also, the experimental results on actual bare charges are variable, and nothing better than 10 per cent accuracy can be given for the peak pressure-radius curve for a given tonnage, or a 20% accuracy in estimating the tonnage from a known pressure-radius curve.

The disadvantage of (2) is that the mathematical difficulties are very great, and complete confidence cannot be placed in the results so far obtained. Further, the results apply only to "free-air". The complicated shock wave patterns caused by the proximity to the ground cannot be introduced into the theory.

The tonnage corresponding with the theoretical curve is found by dividing the energy released by the detonation energy of T.N.T. However, the energy released by a T.N.T. explosion in air is to some extent augmented by after burning of the products. No doubt this is the principal reason for the divergence between the two methods.

The simplest procedure, and the one actually adopted here is to use the experimental results on small charges. A report O.S.R.D. 4076 by A.H. Taub gives a valuable series of curves for the peak pressure on the ground for explosion of unit weight of T.N.T. above the ground. The appropriate curves were selected and scaled up to fit as well as possible the observations in Hiroshima and Nagasaki. The best fit appears to be $W = 5,000$ tons for Hiroshima and $W = 20,000$ tons for Nagasaki. Since the heights of detonation were 1850 and 1800 ft respectively, we have in the two cases

$H/W^{\frac{1}{3}}$ = 8.3 (Hiroshima)

$H/W^{\frac{1}{3}}$ = 5.1 Nagasaki.

Using Tawb's curves, we have the following expected values

<u>Hiroshima</u>

Rft.	900	1120	1570	2240	3140	3810	4480	6100
P p.s.i	22.6	20.6	16.5	13.2	9.5	7.2	5.5	4.3

<u>Nagasaki</u>

Rft	2500	2830	3540	4240	4950	6000	7080	8500
P p.s.i.	23	20.7	14.5	10.5	8.1	5.7	4.4	3.3

The observations to be fitted are as follows

Summary of Results Hiroshima

Distance Feet from X	Peak Pressure p.s.i.	Method of Determination
0 600	35(1) 25	Dishing of safe door Failure of glass panel.
900	18	Crushing of 40 gallon gasoline drums
1000	35	Crushing of drain pipe (unreliable)
1000	20	Dishing of Reinforced Concrete Panel
1900	15	Yielding of vertical I beam.
2100*	15.4	Yielding of steel flag pole.
3200*	9.2	Yielding of steel flag pole.
3600	7.5	Yielding of a wrought iron ladder
3800*	6.6	Failure of wooden floor
4100	5.5	Crushing of a tin can (machine oil can).
5000	3.7	Dishing of top of office cabinet
5000	3.2	Crushing of a blue print drum
6500	1.4	Visual estimate
12000*	0.5	Failure of side-on paper panels
15000	0.28	Failure of wall of timber storage barn.

* Values marked with an asterisk are considered the most reliable.

(1) Estimated value which the writer believes will be confirmed by ~~later~~ better experimentation. This will be undertaken later.

Summary of Results Nagasaki

Distance from X feet	Peak Pressure p.s.i.	Method of Determination
1200	100	Collapse of earthenware drain pipe.
2300*	~~40~~ 35 (1)	Dishing of top of tool chest
3400	16	Snapping of a telegraph pole
3800	14	Crushed Can.
4050*	12.5	Dishing of reinforced concrete floor panel
4700	8.5	Overturning of memorial stones
8000	3- 3.5	Collapse of 4 gallon gasoline cans
12000	1.4	Visual estimate
22000	0.45	Wall of barracks at Kamigo

* Values marked with an asterisk are considered the most reliable.

(1) Estimated value which the writer believes would be confirmed by better experimentation. This will be undertaken later.

The way in which these expected curves fit to the actual observations is shown in Figures 12 and 13. It will be noticed that the observed curves fall away more quickly than the expected curves. This effect is believed to be real, and represents the absorption of energy from the blast wave in causing destruction. Furthermore, the fit at the high pressure end is not (very) good, and the writer is not quite certain how the observed curve should be drawn. Possibly also Taub's curves are in error; the experimental results are not always reliable near the flame zone.

Using Taub's Figure 11, the free air pressure at 1850 ft from 5000 tons is 11.3 p.s.i. On impact at a rigid wall (the ground), the pressure would rise to about 28 p.s.i. This agrees fairly well with the estimated 35 psi from the safe doors. ~~We must therefore either reject the observation on the safe door (50 p.s.i.) or else allow it and say that the heat of the radiation or further shock reflections inside the building put up the pressure to about 50 p.s.i. It may be necessary to repeat~~ The experiments on the safe door should be repeated with a scaled model, using a better experimental arrangement for applying a uniform load. Wet sand is not very satisfactory; an air balloon would be much better, and the set-up so far used was not as good as one would like.

In Nagasaki, the pressure on the ground undoubtedly reached 150 - 200 p.s.i. According to Taub's Figure 11, the pressure at 1800 ft in free air from 20,000 tons is 50 p.s.i. On impact at a rigid wall (the ground) this would rise to 150 - 200 p.s.i. This agrees with the observations on the earthenware drain pipe and on the dished tool chest.

To summarise, we may say that the observations show that the blast equivalent in Hiroshima was 5000 tons and in Nagasaki was 20,000 tons. These figures may be compared with those obtained by comparing the I.B.M. calculations with the air- gauge measurements of Alvarez. The figures quoted are 5000 and 15,000 tons respectively. (1 ton = 2240 lb) The agreement is satisfactory, especially when the two following points are considered

(1) The pressure pulse from the Nagasaki must have passed through several hundred feet of cloud before reaching the gauge. This would probably decrease the magnitude of the pulse.

(2) The I.B.M. calculations do not agree very well with Figure 11 of Taub's paper, although the agreement is fair at large distances. However, the I.B.M. run has been taken much further than Taub's curves, and one cannot be sure that the I.B.M. run really represents high explosive curves. In any case, our estimates are based on figures in the high pressure region (20 - 2 p.s.i.) and the agreement here is not good. ~~To illustrate the discrepancy between Figure 11 and the I.B.M. run, we give the following figures:~~

~~According to the I.B.M. run for 13,000 tons, the over pressure is 1 atmosphere or 14.7 p.s.i. at R = 465m = 1526 ft. The corresponding value of Z in Figure 11 is 4.95, and the overpressure is 50 p.s.i. Again the I.B.M. run gives 2 p.s.i. at 1620m = 5300 ft. The Z value is 17.3 and the corresponding overpressure is 3 p.s.i. At the 1 p.s.i. level, the I.B.M. gives 2800 m = 9200 ft, and Z = 29.8. Figure 11 gives 1.5 p.s.i. Hence, the discrepancy is decreasing but there seems no reason why the two curves should be equivalent at the 0.4 p.s.i. level,~~ Clearly, further theoretical work is necessary. Until this work is performed we prefer to use only experimental curves on high explosive in forming our estimates of the tonnage blast equivalents.