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CONFINEMENT OF AN EXPLOSION BY A STEEL VESSEL

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ABSTRACT

The preliminary data and the theory leading to the accepted design of the elongated confining vessel known as "Jumbo" are discussed. It is shown that the expansions observed in small vessels used to confine explosions of pentolite were consistent with the following pressures and impulses:

Peak reflected pressure	$2200\ W/R^3$ psi
Reflected impulse	$0.4\ W^{2/3}/R$ psi second

Here W is the weight of explosive in pounds and R is the distance from the center in feet. In these small vessels the charge varied from 1 to 4 pounds per cubic foot and the value of $W^{1/3}/R$ varied from 2 to 3. These values were obtained for pentolite but are believed to be roughly correct also for Composition B and torpex.

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CONFINEMENT OF AN EXPLOSION BY A STEEL VESSEL

PART I. - STUDY OF A MODIFIED JUMBO UTILIZING DUCTILITY AND INERTIA OF METAL

This memorandum treats the two problems of confining vessels, namely the supporting of shock forces too high for mechanical strength alone, and the second problem of supporting also the sustained pressure due to the severe confinement. A spherical vessel constructed of high-strength steel does not solve these problems. It appears that the solution of the combined problems may lie in attempting a large reduction in the sustained pressure through (1) increased volume, and (2) further reduction of internal pressure and temperature by imparting energy through a ductile shell to a surrounding mass.

Since most evidence indicates peak pressure of shock far too great to be supported by simple mechanical strength of any practicable container, attention is directed toward making better use of inertia and ductility. A suggested design for accomplishing this is an elongated Jumbo, comprising a heavy, cylindrical central section with lighter, hemispherical ends, all of ductile steel and not cast. The aim is for a practicable type of construction, with welded joints at relatively thin sections.

In Part II, a method of analysis is presented for taking account of inertia and ductility. It is a step-by-step method which has been used for interpreting past performance of Jumbinos. The method may prove especially useful when specific pressure-time curves of blast and specific stress-strain curves of metal are known.

In Part III, the pressures and impulses encountered in tests on small-scale "jumbinos" are given.

BLAST PRESSURES AT CLOSE DISTANCES

No satisfactory records were found of blast pressures measured for such large charges (or close distances) as are contemplated for Jumbo. If the intensity of the charge is expressed as $Z = \sqrt[3]{W}/R$, most records are reliable in the range of Z from about 0.01 to 0.5, while our Z value is 3.4 (4900 pounds at 5 feet minimum distance from center). Therefore, all derivations of probable pressures are extrapolations.

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British Results (R.C. 288)

The British results for Z values from 0.02 to 0.20 developed a seemingly reliable formula for blast pressure in that range as follows

$$p = a,Ze^{b\sqrt{Z}}$$

where a, and b, are constants which are 19.9 and 5.48 respectively for tetryl. If the formula is used with these constants, the pressure for our Z of 3.4 turns out to be 16,000 p.s.i. before applying the factor of 8 to 11 for reflection. Similar pressures are computed for other explosives, and all appear to be unreasonably high.

British Flame-Front Pressures (R.C. 288)

The British results from flame-front velocities dip to the other extreme and predict pressures of only 2000 p.s.i., at Z = 3.4 (again before applying the factor of 8 to 11 for reflection). Later flame-velocity measurements confirming these are reported in a British document summarizing results up to Jan. 31, 1943. These results might be expected to be applicable because they actually were obtained at Z values up to about 2. But according to the theory they appear to be hydrostatic pressures in the shock wave and do not take account of ejected particles in motion and their effect on striking a wall. There must, however, be some significance to the fact that flame-front measurements show only slight increases in pressure as the Z value increases from about 0.5 toward our Z of 3.4.

P.P.A.B. Predictions of Pressure

The charts published by the Committee on Passive Protection Against Bombing (Terminal Ballistics and Explosives Effects) were not intended for application to extremely intensive blasts, but when extrapolated indicate a side-on pressure of 150,000 p.s.i. for Z = 3.4 (our case). This pressure is not unreasonable, provided the duration is consistently small, even when multiplied from 8 to 11 times due to reflection. Such a pressure can be absorbed by the inertia of a steel shell of favorable mass, strength, and ductility.

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WOODS HOLE BLAST-PRESSURE REPORTS

Measurements of blast pressures at close distances were made at Woods Hole, but the largest Z value was nevertheless only 0.82 as compared with our 3.4. The side-o pressure for Z = 0.82 was found to be 705 p.s.i. Over the range of Z values included in the Woods Hole tests, the pressure appeared to increase about as the square of Z (117 p.s.i. for Z = .33, and the 705 p.s.i. for Z = .82). On this basis, the side-on pressure corresponding to our Z of 3.4 would be 12,000 p.s.i. After applying a factor of 8 to 11 for reflection, this pressure appears the most reasonable of all.

IMPULSE

British Results

The British formula derived from measurements at small Z values and for P.A.G. only, yields an impulse of 3.1 pound seconds per square inch for Z = 3.4 and a weight of 4900 lb.

P.P.A.B. Predictions of Impulse

The charts of the P.P.A.B. committee confirm the British formula and predict an impulse of 3.2 for Z = 3.4 and 4900 lb. of H.E. In both cases the reflection factor must be applied, because the pressure is expected to be increased from 8 to 11 times, while the duration remains unaffected by reflection.

Woods Hole Results on Impulse

The Woods Hole measurements of impulse agree with others at the greater distance (247 grams of H.E. at 30 inches), but show surprisingly little change in impuls at the shorter distances which were not investigated by others. For example, a slightly lower impulse was observed at 12 inches than at 18 inches, for the fixed charge weight of 247 grams.

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Reflection Factor of Pressure and Impulse

Several authorities agree that the multiplication of pressure due to reflection of a blast wave from a flat and rigid face obeys the Hugoniot equation as follows:

$$P_f = 2\ P_s\ \frac{103 + 4\ P_s}{103 + P_s}$$

where P_f is face-on pressure and P_s is side-on pressure. It is apparent that for high pressures such as those encountered in Jumbo, the formula gives a limiting face-on pressure of 8 times the side-on pressure. This applies to a specific heat ratio of 1.4 only; it may be possible to reach a multiplication as high as 11 times for a lower specific heat ratio such as might prevail in the flame region.

The duration of pressure is not believed to be affected by simple reflection at normal incidence, so impulse is increased by the same factor as is pressure due to the reflection.

In case the blast wave strikes a wall at other than normal incidence, the action is complex and no simple law explains the phenomenon. For very low pressures, the multiplication is greatest at near-glancing angles (about 10° with the wall). For intermediate pressures, the multiplication is greatest at an angle of about 45°, but it should be recognized that the amplification is not sufficient to prevent pressures from falling off with angle when a charge is exploded in front of a wall, because the effect of increasing distance more than offsets the effect of obliquity even in the region of greatest "obliquity excess".

The foregoing discussion on effect of obliquity on blast pressure is based entirely on Von Neuman's "Oblique Reflection of Shocks".

DESIGN OF JUMBO

Several considerations seemed to point to an elongated containing shell having a cylindrical central portion and spherical ends. The possible advantages were as follow

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1. Increased volume and lowered equilibrium pressure.
2. Welding could be done at thinner and less critical sections.
3. Laminated central section could be used, facilitiating manufacture, avoiding casting and allowing use of more ductile steel.
4. Ductility increased further by subjecting critical central region to uniaxial instead of biaxial stress.
5. No critical region was weakened due to discontinuity of mass and section at manhole.

The following derivations begin by being general and later are restricted to apply only to a cylinder subjected to internal pressure. The deformations are so large for the present application that the cylinder is assumed to behave plastically, such that the simple thin-cylinder formula holds for the relation between internal pressure and hoop stress. It is assumed that the blast pressure is absorbed by the inertia of the steel and all of the impulse is used to set the steel into motion in an outward radial direction without substantial resistance being offered at this stage by the mechanical strength of the shell. Immediately the impulse is over, the mechanical strength of the shell is assumed to begin absorbing the kinetic energy of the steel until the outward motion has stopped and the steel has stretched (possibly by several per cent). More refined analyses are carried out later which avoid the errors due to separating the action into the two resisting phases of fast acceleration and a slower deceleration. It is necessary for safe action of the shell that the impulse is absorbed before the outward expansion has exceeded a fair fraction of the total expansion available before failure, as can be seen from the equations below.

First, the blast pressure accelerates the steel shell outward according to the formula

$$F = ma = \frac{W}{g} a$$

where F is the force on each square foot, W is the weight of one square foot of the shell, "g" is 32.2 feet per second per second, and "a" is the acceleration in feet per second per second.

The consequent radial velocity is then

$V = aT = \frac{32.2FT}{\text{[illegible]}}$ where T is the time in seconds.

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By definition, FT is the impulse A, provided that F is the average pressure (or about half the peak press.) Making this substitution and solving for kinetic energy

$$V = \frac{32.2A}{W} \text{ and } 1/2\ MV^2 = \frac{16.1\ A^2}{W}$$

This kinetic energy which was accepted suddenly, can be absorbed rather slowly if the energy required to stretch the shell to its safe limit is sufficient. Thus

$$\frac{16.1\ A^2}{W} = F_2 RE$$ where F_2 is the radial resisting force, R is the mean radius and E is the elongation ratio of the metal (RE is increase in radius).

But for a plastic cylinder

$$F_2 = \frac{ts}{R}$$ where S = tangential stress in shell

Then $$\frac{16.1\ A^2}{W} = tsE$$

If S is assumed to be $5.76\ 10^6$ p.s.f. (= 40,000 p.s.i.) and constant in this plastic range, and if W = 490t, then

$$t = \frac{7.55.10^{-5}A}{\sqrt{E}}$$

This equation reveals that the thickness of the cylindrical shell must be increased directly as the impulse is increased. If the impulse is doubled, the thickness must be doubled to maintain a given safety, but the elongation (ductility) would need to be quadrupled to accomplish the same result.

Later analyses employ a step-by-step process wherein the inertia and mechanical forces are considered simultaneously and any stress-strain curve for the metal can be handled.

PART II - METHOD OF ANALYZING JUMBINO

A step-by-step analysis permits determination of the manner by which the impulse of an explosion will be supported by a confining shell. If the impulse were as nearly instantaneous as predicted by most evidence, a simpler analysis could be used. But the analysis described here applies to any shape of pressure-time curve and to any shape

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of stress-strain curve of the metal. This analysis takes no account of vibration, or of reflection of shock waves within the metal itself.

Before beginning the step-by-step computations, the pressure-time curve for the shock and the stress-strain curve for the metal should be prepared. The particular stress strain curve used in this example is one of the earlier ones where the steel was assumed to be elastic to 42,000 p.s.i. (E = 30,000 p.s.i.), and then to stretch linearly to 1 percent as the stress was raised to 75,000 p.s.i. Thereafter, the steel was assumed to stretch without increase in stress.

The pressure time curve used here was one where the maximum (40,000 p.s.i.) occurred instantaneously and then decayed linearly to zero. This example made no allowance for sustained pressure, but it is apparent that the method will apply to any pressure-time curve, whether the pressure drops to zero or not.

The first step is then to compute how far the steel will move outward during an initial, brief interval of time due to the accelerating effect of the net pressure acting for that interval. This movement brings into play an increased mechanical resistance which serves to reduce the effective blast pressure available for accelerating the metal. Thus, for the next brief interval of time, the additional movement is computed from the acceleration during the current interval and from the velocity gained during the preceding interval. The mechanical resistance is again changed and the distance moved during the next interval is computed, again taking account of the velocity carried over from the preceding interval. Such steps are repeated until the outward, radial motion of the metal becomes zero, and the shell begins to collapse. The collapse is not serious, because the plastic deformation has been converted into heat, and only the elastic deformation contributes toward inward motion. The maximum radial movement (per unit of radial distance) represents the elongation of the metal. Measurements on a sphere after an explosion reveal only the plastic portion of the elongation, to which must be added an elastic elongation of usually .20 per cent if the total elongation is desired.

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The details of the step-by-step method may be checked by reference to a sample computation sheet, as in Table 1. The example chosen was a simple one where the total impulse was 3.0 p.s.i. seconds and the peak pressure was 40,000 p.s.i., such that time intervals of 10 microseconds were satisfactory. Each row of figures in Table 1 refers to a single interval of time and in making the computations, one row must be completed before the next can be begun. The first column merely lists the elapsed time in microseconds to the end of the interval in question.

The second column lists the average blast pressure in millions of p.s.f. for the time interval, taken from a curve such as that in the lowest chart of Fig. 3. To avoid confusion, the unit of distance is one foot throughout, and working charts are plotted accordingly, but final results are plotted in terms of inches because of familiarity.

The third column lists the net radial pressure after subtracting the estimated average mechanical resistance for the interval. The estimation of average mechanical resistance before the resistance at the end of the interval is known may appear difficult, but it is not so. High accuracy is not essential in this estimation; if the resistance is overestimated moderately, adequate compensation is accomplished by a similar underestimation for the next interval. If the estimation is seen to be badly in error after the row is completed, it is not difficult to recompute the row.

The fourth column is the acceleration of a mass of shell metal of one square foot inside area due to the net radial pressure in the preceding column. For at steel Jumbino of 12 inch inside diameter and 1.5 inch wall, it is only necessary to multiply the net pressure by 0.54 to obtain acceleration in millions of feet per second per second, as is done in Table 1.

The fifth column lists the velocity in feet per second at the end of the time interval due to the accerleation "a". This is merely the product of acceleration and time, where the time is 10 microseconds.

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The sixth column lists the outward radial distance traveled by the metal due to an average velocity of V/2 in 10 microseconds. This distance is in millionths of a foot.

The seventh column lists the velocity at the beginning of an interval, and is found by adding V and Vo from the previous row.

The eighth column lists the outward radial distance traveled by the metal due to a uniform velocity of Vo during 10 microseconds.

The ninth column lists the total outward radial distance traveled by the metal up to the end of the interval in question, again in millionths of feet. This is found by adding "d" from the previous row and "d", and Dd_v" from the current row.

The final column lists the radial mechanical resistance per sq. ft. of inside area due to the radial movement in the ninth column. If "d" is divided by the radius, it becomes the strain, or elongation of the metal. The corresponding stress can be taken from the stress-strain curve. The corresponding radial pressure is then found by dividing the proper factor, in this case 2 (in the case of a cylinder of equal thickness-radius ratio, the factor is 4). Actually, the factor is not exactly 2 and it varies slightly when the metal reaches the plastic region, but the use of a fixed factor of 2 is consistent with the accuracy desired or obtainable in the computations in the light of present knowledge. In the case of a 12 inch Jumbino, the radius is 0.5 feet, so "d" may be considered to be half the strain, and since half the stress is desired, it can be ready directly from the stress-strain curve, calling "d" the strain. That is to say, half stress is the equivalent radial pressure and so for this special case, no factor need be applied to the stress due to the half-strain "d" to obtain radial pressure equivalent. The average mechanical resistance for an interval is the average of the "p" in that row and the one in the preceding row, and this average is to be subtracted from F_o in the next row to obtain the new F_n.

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The significant quantity in Table 1 is the radial distance as shown in the ninth column. It is only necessary to double the values listed there to obtain elongations (or strain) of the metal, since the radius is 0.5 feet. The figures in the ninth column indicate that the radial movement increased to a maximum of about 2500 millionths of a foot and then receded. The unit elongation was then .0025/0.5, or .0050, the quantity sought.

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TABLE I

SAMPLE OF STEP-BY-STEP COMPUTATION FOR JUMBINO

T	F_o	F_n	a	V	d	V_o	d_v	d	p
10	5.27	4.97	2.68	26.8	134	0	0	134	.58
20	4.50	3.10	1.68	16.8	84	26.8	268	486	2.10
30	3.75	1.25	0.68	6.8	34	43.6	436	956	3.18
40	3.00	-0.30	-0.16	-1.6	-8	50.4	504	1452	3.45
50	2.25	-1.35	-0.72	-7.2	-36	48.8	488	1904	3.70
60	1.50	-2.30	-1.24	-12.4	-62	41.6	416	2258	3.90
70	0.75	-3.25	-1.76	-17.6	-88	29.2	292	2462	4.00
80	0	-4.00	-2.16	-21.6	-108	11.6	116	2470	4.01
90	0	-4.01	-2.16	-21.6	-108	-10.0	-100	2262	
100	0								

T = Time to end of interval in microseconds.

F_o = Average blast pressure during interval, millions of p.s.f.

F_n = Net pressure, F_o less mechanical resistance

a = Acceleration in millionths of ft. per second per second,

V = Velocity increase during interval, ft. per second.

d = Distance moved during interval due to V only, millionths of a foot,

V_o = Initial velocity at beginning of interval, ft. per second.

d = Accumulative distance moved to end of interval, millionths of feet.

d_v = Distance moved during interval, due to V_o only, millionths of a foot.

p = Radial pressure (mechanical resistance) due to movement d, millions p.s.f.

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PART III - PRESSURES AND IMPULSES DUE TO HIGHLY CONFINED EXPLOSIVES

A pressure vessel was designed in the summer of 1944 to confine two tons of explosives. Since insufficient data were available on pressures and impulses under such conditions, studies of these properties were made for design purposes. The most reliable data were obtained from measured expansions of small vessels, which were tenth-scale models of spherical and elongated prototypes, respectively. The data so obtained are presented on the following pages and supercede those mentioned for sake of background at the beginning of Part I, and other data which were available at the time when Parts I and II were originally written.

DETAILS OF VESSELS

A number of small, spherical vessels were tested as tenth-scale models of a prototype which was never constructed. They were made of cast steel in two grades, one having a yield point, in static test, of 30,000 p.s.i., and the other 60,000 p.s.i. The inside diameter was 12 inches and the wall thickness was 1.5 inch.

The tenth-scale models of the elongated prototype called "Jumbo" comprised a central, cylindrical section 18 inches long, with hemispherical ends. The inside diameter of the cylindrical section and of the hemispherical ends was 12 inches. The wall thickness of the cylindrical section was 1.2 inch (two layers 0.6 inch each) and of the hemispherical ends 0.6 inch. The wall thickness of 1.2 inch for the cylindrical section was not to full scale of Jumbo as built, and later models yet to be tested have the proper wall thickness of 1.5 inch. The metal was 1015 to 1020 mild steel, which was annealed after having been forged, machined and welded. The dynamic analyses which were made apply only to the central portion of the cylindrical section of these elongated vessels, where the distance from the center of the charge to the wall was 6 inches and the wall thickness was 1.2 inch. The volume of the small, elongated vessels was 1.7 cubic feet.

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ASSUMPTIONS

The shock pressure due to a charge within a vessel was assumed to rise instantaneously to its peak value and then to decay linearly with time. This was admittedly inaccurate, but the error due to this simplification was believed to be only a few per cent. Only reflected pressures were considered and no data were obtained concerning "side-on" pressures in this study. The impulse was assumed to be simply one half the product of peak pressure and duration, assuming further that the duration was the time required for the pressure to decay linearly to zero.

The rapid-loading properties were not measured on the steel in the vessels, so they were estimated from the static tests in accordance with the findings of Duwez and Clark at C.I.T. The yield point was taken as 80,000 p.s.i. for the spherical vessels of alloy steel (static yield point 60,000 p.s.i.) and 60,000 p.s.i. both for the elongated vessels and for those spherical vessels which were of mild steel (static yield point 30,000 p.s.i.). The elastic modulus was taken as 30,000,000 p.s.i. up to the yield point, beyond which elongation was assumed to occur without change in stress.

OBSERVED RESULTS

The spherical vessels were intended for 4.5 lb. of H.E., but they failed at about 2 lb. The expansion results on vessels which did not fail can be summed up by stating that 1.75 lb. of Pentolite caused a linear (radial) expansion of 0.3 percent, including the elastic expansion of 0.2 percent, and that the expansion increased rapidly for higher weights of charge. Charges less than 1.75 lb. left no permanent expansion.

The elongated vessels were more ductile, and large expansions were obtained without failure. In one case, where part of a charge detonated in a hemispherical end, an average elongation of 12.6 percent was measured over the pole, with a maximum of at least 20 percent. Typical elongations measured at the central band (where analyses were made) are shown in Table 1. The low expansion for 2 lb. of Torpex and the high expansion for 3.5 lb. are consistent with the facts that the lower peak pressure of Torpex governs for low charge weights, and the higher static pressure of Torpex governs for high charge weights.

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TABLE I

Observed Expansions of Central Band of Elongated Vessels

Charge Weight	Expansion	Remarks
2 lb. Pentolite	1.0 percent	New vessel, fair test
3.5 lb. Pentolite	2.2 "	Second test, part of charge dropped and detonated separately
3.5 lb. Pentolite	2.9 "	Third test, probably reliable
2 lb. Torpex	0.8 "	First test, new vessel
3.5 lb. Torpex	3.8 "	Second test

Static or "sustained" pressures were measured and computed as an auxiliary part of the study. They played an important part in the behavior of vessels, especially when the charge weight was enough to make the static pressure approach the yield strength of a vessel. Best measurements were obtained on Composition B, two values being obtained which checked one another and the theoretical value as well. The pressures due to TNT, Pentolite and Torpex were estimated from the Comp. B value on the basis of relative caloric energies. The pressures below are believed accurate within about 5 per cent and are listed as the partial pressures due to each pound of H.E. per cubic foot of space.

Composition B(measured and comp.)	3000 p.s.i. per lb/cu.ft.
TNT	2700 p.s.i. per lb/cu.ft.
Pentolite	2800 p.s.i. per lb/cu.ft.
Torpex	3750 p.s.i. per lb/cu.ft.

The above pressures are not "static" in the ordinary sense, because they decay rapidly due to cooling. Although the "static" pressure does not decay substantially during the fraction of a millisecond of outward motion of the vessel shell, it nevertheless drops by several per cent in the first one tenth second.

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ANALYSIS OF MEASUREMENTS

Peak pressure and impulse go hand in hand. Almost equally good agreement between analysis and experiment can be obtained by a variety of combinations of pressure and impulse. That is to say, if one chooses a too-high peak pressure, it can be compensated fairly well by choosing a correspondingly too-low impulse. The following equations for impulse and peak pressure appear to give the best over-all agreement between computed and observed expansions of vessels, when the computations are based on the static pressure and strength data given above.

$$\text{Peak Pressure} = 2200\ W/R^3 \text{ lbs. per sq. in.}$$

$$\text{Impulse} = 0.4\ W^{2/3}/R \text{ psi seconds}$$

In these equations W is in pounds and R is in feet, although pressure is in pounds per square inch and impulse is psi seconds. The equations apply best to Pentolite and <u>include</u> the reflection factor, which is estimated at 11 for the high confinement.

The peak pressure given above is somewhat higher than is obtained by measurement of flame-front velocities, but it is far lower than is obtained by extrapolating from blast-gage measurements at greater distances.

The impulse given above is lower than would be obtained by applying a reflection factor to the long-established relation which applies reliably for the ordinary range of impulses. In other words, the usual equation for side-on impulse due to G.P. bombs is

$$A \text{ (impulse)} = 0.055\ W^{2/3}/R$$

When this is corrected to the double weight of bare charges over G.P. bombs, the impulse becomes $0.087\ W^{2/3}/R$. And when a reflection factor of 11 is applied, it becomes $0.95\ W^{2/3}/R$. Thus, this extrapolated impulse is more than double that found most applicable to the behavior of vessels with internal charges (0.95 : 0.40). The lower impulse is believed to be necessary and sufficient, because when the extrapolated impulse is used, it is impossible to get agreement between observed and computed expansions of vessels without resorting to unreasonable strength and static

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The few comparative tests which were made showed qualitatively very little difference between Composition B, Torpex and Pentolite as far as peak pressure and impulse was concerned. The main difference was in static pressure, where the range was 40 percent, from TNT (low) to Torpex (high). There was some evidence that the peak pressure due to Torpex was low, as is truly the case at greater distances with charges unconfined.

STATUS OF JUMBO AS OF AUGUST 27, 1945

On August 27, 1945 R. W. Henderson completed a check on the present condition of Jumbo. The vessel was not damaged in any way by the July 16 blast and a transit survey shows it to be absolutely verticle on its foundations.

Henderson has fabricated and installed a heavy weather-tight manhole cover for the opening and covered this in turn with a tarpaulin held in place by steel banding tape. This should insure against corrosion damage for as long as this project will have any interest in the vessel.

All of the component parts of the vessel closure were cleaned, thoroughly greased, crated and then stacked on 6 x 6 sleepers in the field back of the Fubar warehouse at Trinity. Each of the four boxes is labelled with its contents, and the entire stack is covered by a tarpaulin held in place by steel banding tape. A sign board was then attached to this stack identifying the contents.

This information is given here as a matter of record in the event that someone may conceive an experiment which would require the use of the vessel.

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