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NAVORD REPORT 6234

THE CONTRIBUTION OF AFTERBURNING TO THE AIR BLAST FROM EXPLOSIVES (U)

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22 MAY 1959

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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Prepared by:
Calvin C. Hatle

Approved by: [signature]
E. M. FISHER, Acting Chief
Air-Ground Explosions Division

ABSTRACT: It is well known that most pure organic explosives lack sufficient oxygen within the explosive molecule to fully oxidize the combustible material present in the explosive. Studies have shown that explosives of this type, termed oxygen deficient explosives, can react after detonation with oxygen in the ambient atmosphere (afterburning process) and in so doing can contribute additional energy to the blast wave. The present study has developed data on this process as a function of the degree of oxygen deficiency of the explosive and the concentration of oxygen in the test gas surrounding the explosive. The explosives used were TNETB (slightly oxygen deficient), RDX (moderately deficient), and TNT (highly deficient). The test gases were nitrogen, air, and oxygen. The air blast performances of these explosives were measured and relative values of the air blast energies in terms of equivalent weights (EW) were determined. The following table gives the results:

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EW Values Relative to TNETB Fired in N_2 Test Gas

Explosive (Oxygen Deficiency)	Test Gas	EW_P (Pressure Basis)	EW_I (Impulse Basis)
TNETB	N_2	1.00	1.00
(Slightly Deficient)	Air	1.02	1.03
	O_2	--	--
RDX/Max (98/2)	N_2	0.86	0.84
(Moderately Deficient)	Air	1.07	1.24
	O_2	1.13	1.51
TNT	N_2	0.72	0.70
(Highly Deficient)	Air	0.90	1.07
	O_2	0.99	1.39

The afterburning contributions to the air blast performance are seen to vary appreciably with both explosive oxygen deficiency and oxygen concentration in the test gas. These contributions range from the very small values of 2-3% for TNETB up to the very large value of 99% for TNT fired in oxygen. As a consequence of the contributions from afterburning the order of merit of the test explosives varied with the ambient gas. In nitrogen gas TNETB is superior to both RDX and TNT while in air and oxygen RDX is superior to both TNETB and TNT.

A correlation of the EW results with heats of detonation yielded a direct proportionality between the EW's in nitrogen (no afterburning) and calculated heats of detonation using the water decomposition mechanism (H_2O (g), CO, CO_2 mechanism). On the basis of this correlation, a simple analytic method was formulated for determining the equivalent weights of pure organic explosives fired in inert gases. It is anticipated that this method will be useful in predicting the air blast performance of explosives at high altitudes (where the afterburning effect is expected to be negligible). The method may also be of value in determining heats of detonation of organic explosives from measurements of their blast performances in nitrogen. An extension of this analytic method was made to account for the increases in blast performances obtained from the afterburning process.

The results of this study do not in any manner change previously established concepts or data on blast effects in air; however, they do provide a better understanding of these effects in terms of heat energy release.

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This study of the contribution of afterburning to the air blast performance of explosives is part of the Explosions Research Department's comprehensive program of investigation into the fundamental properties of chemical high explosives. This study is submitted as a partial solution to the key problem in explosives research and developments, as set forth in NAVORD 3906, entitled, "Develop Improved Explosives to Increase Lethality of Air Defense Weapons".

This work was performed under NOL Task No. 301-664/43007/01, Explosions in Air.

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MILL A. PETERSON
Captain, USN
Commander

C. J. Aronson

C. J. ARONSON
By Direction

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I. [redacted]

It is well known that many [redacted] explosives do not contain sufficient oxygen within their molecule for the complete oxidation of the combustible material present in the explosive. As a result, these explosives (termed oxygen deficient explosives) have heats of detonation that are smaller than their heats of combustion. A good example of this is found in TNT ($C_7H_5N_3O_6$). This explosive requires a total of 16.5 moles of atomic oxygen for the complete oxidation of a mole of explosive material; it is seen, however, that only 6 moles of atomic oxygen are contained per mole of explosive. Consequently, the heat of detonation for TNT is much smaller than the heat of combustion--the former being about 224 kcal/mole whereas the latter is 792 kcal/mole.

In detonation processes involving explosives of this type, the possibility then exists for augmenting the heat of detonation by oxidizing the detonation products through contact with oxygen in the surrounding medium. This process of increased oxidization of the detonation products is termed afterburning. That this process could actually occur, and, more important, could contribute to the blast energy of an explosive, was conclusively demonstrated in two experimental studies conducted during World War II (1), * (2).

The present study was undertaken to advance the understanding of this process and its effect on the air blast performance of explosives. The first part of this report describes the experimental phase of the study. This phase consisted of a field program designed to determine the effects of afterburning on the air blast performance of explosives having different degrees of oxygen deficiency, fired in test gases having varying degrees of oxygen concentration. The second part of the report presents an analysis of the afterburning effects, including correlations with explosive heat of detonation and oxygen balance.

* Numbers in parentheses refer to list of references on pages 25 and 26.

II. EXPERIMENT

Experimental Method

Explosives covering a range of oxygen deficiencies were fired in three test gases, consisting of pure oxygen, air, and pure nitrogen. The oxygen and nitrogen gases were contained in neoprene balloons. The air blast performances of these explosives were determined and the results for the air and oxygen series of tests were compared to those obtained in the nitrogen series (i. e., those excluding afterburning). By this technique the effects of afterburning could be directly ascertained as functions of both the explosive oxygen balance and the oxygen concentration in the test gas.

Test Explosives

The test explosives used were TNETB, RDX/Wax (98/2) and TNT (see Table I). These explosives ranged in degree of oxygen deficiency from the slightly deficient TNETB, through the moderately deficient RDX, to the greatly deficient TNT. Quantitative values of these deficiencies are generally expressed in terms of the oxygen balance, which is defined here as the amount of oxygen, in grams, contained in one gram of explosive in excess of the amount needed for the full combustion of the explosive material. By this definition, the oxygen balance for an oxygen deficient explosive will have a negative value. For the test explosives the oxygen balances are -0.04, -0.28, and -0.74 for TNETB, RDX/Wax, and TNT, respectively.

The explosive used as a control for the experiment was cast Pentolite.

Techniques of Measurement

Shock wave peak pressure and positive impulse were the parameters on which the air blast performances of the test explosives were established. The peak pressure, defined as the maximum overpressure in the shock wave, was determined by the velocity method. The shock wave velocity and the speed of sound were measured by recording arrival times at nine face-on tourmaline piezoelectric gages (see Figure 1). The speed of sound was determined by the two-gage method, which also provided

information for a wind speed correction to the shock wave velocity. Peak pressures were calculated using the Rankine-Hugoniot equation relating shock velocity to peak pressure. For details on instrumentation and methods see (3).

Positive impulse is defined by the time integral $\int_0^{t_+} p\,dt$ where p is the shock wave overpressure at time, t, and t_+ is the duration of the positive phase of the blast wave. Included is the contribution to the impulse made by that portion of the secondary shock for which the pressure is in excess of atmospheric pressure.* The positive impulse data are obtained from mechanical integrations of pressure-time records obtained from eight tourmaline gages (see Figure 2). The pressure scale for the records was established using the peak pressures obtained from the velocity method. Corrections to the recorded peak pressures on the records were made to account for the effect of finite gage size. For details of the pressure-time recording equipment, see (4) and (5).

Figures of merit of the air blast performances of the explosives were obtained from the pressure and impulse data as follows: The mean values of peak pressure were plotted on log-log graph paper as functions of reduced distance, λ (distance from the charge in feet divided by the cube root of the charge weight in pounds). Then, using methods described in (6) and (7), the weight of that explosive taken as the standard was determined that would produce the same peak pressure at the same distance as that obtained from the test explosive. This figure of merit is termed the equivalent weight on a pressure basis (EW_p).

A corresponding figure of merit was obtained using graphic plots of the reduced impulse data (positive impulse divided by the cube root of the charge weight) vs reduced distance. This figure is termed equivalent weight on an impulse basis (EW_I).

One other figure of merit was obtained, this one being determined from the impulse data excluding the contribution of the secondary shock. This figure of merit is designated as EW_{II}.

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* Calculations were also made of the positive impulse excluding the contribution of the positive phase of the secondary shock.

[redacted] Charges Using Balloons

The charges fired within balloons were hung as shown in Figure 3. To position each charge precisely in the center of the balloon, two cords of equal length were affixed to the charge harness. The charge was then placed within the balloon and the two cords fastened to the balloon, one at the neck, the other at a hole formed at a point diametrically opposite to the neck. The two holes were sealed and the balloon inflated. Suspension lines attached at the two ends were then used to position the system relative to the gages.

This method provided a precise and unvarying centering of the charge within the balloon. Also, since the balloons were translucent, the charges could be accurately positioned with respect to the gages by the use of a transit, sighting on the charge within the balloon.

The balloons were neoprene *3-300* and *3-500* balloons, weighing 300 grams and 500 grams, respectively, and manufactured by the Davy and Alay Chemical Company. Since the internal pressure obtained in the inflated balloons was only 1 mm over the ambient air pressure, it was neglected in the program. Figure 4 illustrates the field arrangement for a typical balloon shot.

Properties of Gases

Nitrogen was used rather than an inert gas or carbon dioxide as the atmosphere for those shots designed to exclude afterburning. This gas was chosen because its thermodynamic properties are closer to those of air than are those of either the inert gases or carbon dioxide, which have specific heat ratios and densities appreciably different from those of air.

The nitrogen was obtained from compressed gas bottles. Its purity was 99.9%. Calculations showed that the amount of oxygen available for afterburning in the nitrogen shots (consisting of the oxygen impurity in the gas plus the oxygen in the entrapped air in the balloon) was about one gram, or less than 1/5% of the amount of oxygen contained in each ton explosive. The effects of these impurities were thus ignored in the study.

[redacted] indicates that R_2 is a product of detonation of pure organic explosives and that the R_3 in the atmosphere takes no part in the afterburning reactions.

The shots in air atmospheres were made without balloons, except for one series of shots which used balloons inflated with bottled air (see section on Balloon Effects).

In addition to the series of shots fired in nitrogen and air, a series was fired in atmospheres of pure oxygen. The oxygen was obtained from compressed gas bottles, the purity being 99.5%. The impurity, consisting mostly of nitrogen, was considered to be insignificant for the purposes of this study.

Charges

The charges were 3-1/4 inch diameter spheres with nominal weights of one pound. All the test charges were centrally initiated with engineer special detonators without the aid of boosters.

Data on the charges are given in the following table:

Composition	Parts by Weight	Loading	Weight (gms)[1]	Density gm/cc	%[2] T.M.D.
[redacted]	100	Pressed	418.0	1.48	83
[redacted]/Wax	98/2	Pressed	413.7	1.46	83
RDX/Wax	98/2	Pressed	415.5	1.47	83
TNT	100	Pressed	388.6	1.37	83
Pentolite	100	Cast	476.2	1.63	95

1. Variations of charge weights within each group were less than 0.8%.
2. % of theoretical maximum density.

Balloon Effects

Preliminary tests were conducted to determine the effect of the balloon on the air blast performance. Measurements were made of the air blast obtained using cast Pentolite (50/50) in two series of tests. One series was fired in free air without balloons and the other series was fired in balloons containing air.

Measurements were made as described in the preceding sections. Peak pressure and positive impulse data are tabulated in Tables II and III. The pressure data are also plotted on log-log graph paper as a function of reduced distance (Figure 5).

From the pressure data, the equivalent weight was determined for the Pentolite fired within the balloon compared to that fired in free air. This value was 0.96 (i. e., 0.96 pounds of Pentolite fired in free air should produce the same peak pressure at the same distance as that obtained from one pound of Pentolite fired with a balloon). The precision index (standard error) for this equivalent weight was 1.5%. Positive impulse results were calculated only for the two gage positions nearest and farthest from the charge. Since these results revealed no significant difference in the values of reduced positive impulse obtained from the free air and balloon shots, no further analysis was performed on the impulse data.

From the equivalent weight result ($EW_p = 0.96 \pm 0.014$) it seems possible that a small attenuation effect may be present in the balloon shots. However, a general rule, based on the experience acquired in a large number of programs similar to this one, is that a difference of less than 5% in equivalent weight between two explosives can generally be neglected (provided the difference does not indicate or form a definite trend). Using this rule, it was decided to consider the balloon effect to be negligible, and no corrections were made in the program for such an effect.

An effect of interest was obtained in this phase of the program. This was the occurrence of large spurious positive voltage signals in several gages at a time approximately one millisecond after the detonation of the charge. The time of occurrence of this signal corresponded closely to the time of balloon fragmentation. Since the application of electrically conducting paint (graphite base) on the gages eliminated these signals in the gages, it was inferred that the signals were being produced by electromagnetic radiation emanating from the balloon at the time of fragmentation. The source might have been electrostatic charges developed on the balloon during inflation, or perhaps, ionized particles formed during the fragmentation of the balloon.

The free air Pentolite series of shots constituted the control series for the program. The pressure and impulse results obtained from

this series were in good agreement with the results of previous experimental programs using Pentolite, indicating that the present experimental and analytical methods were satisfactory.

Balloon Size Effect

For the series of shots in the nitrogen filled balloons, it was first necessary to determine the balloon size needed to prevent any reaction of the detonation products at a time early enough to contribute to the air blast with the air external to the balloon. The explosive with the greatest expected afterburning (TNT) was selected for this test and a series of shots was fired in nitrogen filled balloons having diameters of zero (free air), 1.5, 3.0, and 4.5 feet. Measurements were made of the air blast performance as described in preceding sections.

The data are tabulated in Tables II, III, and IV and plotted on Figures 6, 9, 12. Equivalent weights were determined, using TNT in the 4.5 foot diameter balloon as a standard. These results are given in the following table:

Balloon Diameter (in feet)	Reduced Radius ($Ft/Lb^{1/3}$)	EW_P	EW_I	EW_{DI}
4.5	2.4	1.00	1.00	1.00
3.0	1.6	1.00	0.99	0.99
1.5	0.8	1.18	1.30	1.26
0	0	1.25	1.53	1.33

These results indicate the cessation of afterburning contribution to the air blast with the use of a 3.0 foot diameter balloon. In order to provide a margin of safety, a balloon diameter of 4.5 feet was used in all subsequent tests.

It is interesting to compare the balloon radius used in this study to those used in the studies of References 1 and 2; since different weight charges were used in the three studies (nominal weights of 0.9, 0.25, and 0.33 pounds, respectively) it is necessary to compare the reduced radii ($r/W^{1/3}$). These values for the three studies are calculated to be 2.4, 1.6, and 2.2 $ft/lb^{1/3}$, respectively. Apparently these

sizes were all sufficiently large, since a reduced radius of 1.6 ft/lb$^{1/3}$ suffices for excluding any air blast contribution from afterburning, when firing TNT in nitrogen.

Using the reduced radii values, it is seen that the afterburning contribution ceases at approximately 1.6 ft/lb$^{1/3}$ (11 charge radii). From this result we can state that the detonation products of TNT, when fired in nitrogen, traverse out to a reduced distance of at least 1.6 ft/lb$^{1/3}$ and are capable of reaction out to this distance; in addition; this reaction can contribute energy to the air blast wave. Beyond 1.6 ft/lb$^{1/3}$ no energy contribution occurs, presumably due to the detachment of the air blast wave from the explosive gas ball.

These distances, of course, apply only to the nitrogen shots; for shots in air or oxygen, the distances could well differ because of the additional reaction of the detonation products due to afterburning. The question then arises whether the 2.25 foot radius balloon sufficed for the oxygen shots. This cannot be answered conclusively; however, it seems reasonable to answer in the affirmative since the oxygen filled balloons contained seven times the amount of oxygen needed for the full combustion of the TNT charges, and eighteen times for the RDX charges.

Results

The main series of shots was fired using TNT, RDX/Wax, and TNETB.* The nitrogen and oxygen series were fired in 4.5 foot diameter balloons and the air series was fired in free air. Peak pressure and positive impulse data obtained from this series are tabulated in Tables II, III, and IV. These data are also plotted on log-log graph paper as a function of reduced distance. Mean values of peak pressure versus reduced distance are plotted on Figures 5 - 8, and mean values of reduced positive impulse versus reduced distance are plotted on Figures 9 - 14. From these data, equivalent weights were determined, taking the performance of TNETB in the nitrogen balloons as a standard of comparison. These results are presented in Table V.

* Due to a change in charge pressing procedures, the TNETB charges in the oxygen series contained 2% wax.

III. ANALYSIS OF THE AFTERBURNING EFFECT

Analysis of EW Results

From the results presented in Table V an evaluation of the equivalent weights can now be made as a function of the oxygen concentration in the test gas. Taking the equivalent weight of each explosive fired in nitrogen as a standard of comparison, the following results are obtained:

Test Gas				
Name	Percent O_2	EW_P	EW_I	EW_{IX}
TNETB				
nitrogen	0	1.00	1.00	1.00
air	23	1.02	1.03	1.03
oxygen[1]	100	1.02	1.18	1.08
RDX				
nitrogen[1]	0	1.00	1.00	1.00
air[1]	23	1.24	1.48	1.32
oxygen[1]	100	1.31	1.80	1.42
TNT				
nitrogen	0	1.00	1.00	1.00
air	23	1.25	1.53	1.33
oxygen	100	1.38	1.99	1.64

1. 2% wax added to charges

From these results, it can be seen that the afterburning effect in air is considerable for both RDX* and TNT. In contrast, the effect for TNETB, an almost balanced explosive, is negligible. For the oxygen series additional contributions are noted for RDX and TNT. These additional increases are less than might be anticipated considering that the concentration of oxygen in the oxygen balloons was four-fold that in air. A comparison for the TNETB oxygen series was not possible since the charges in this series contained wax.

* Unless otherwise noted in the following, "RDX" refers to RDX/Wax (98/2).

The results reveal that the afterburning process has a much greater effect on the positive impulse of the blast wave than on the peak pressure; this is a result that might be expected inasmuch as afterburning is a sustained process and can contribute energy to the blast wave over a sizeable period of its positive phase.

Since TNT has a much greater oxygen deficiency than RDX it might be expected that TNT would show a greater relative improvement in performance than would RDX, when going from nitrogen to air. The results, however, reveal that the relative increases in equivalent weights are about the same for both explosives. It can be inferred from this that the contribution of afterburning in air is by no means simply proportional to explosive oxygen deficiency.

The results of Table V can also be used to evaluate the afterburning effect as a function of the oxygen balances of the test explosives. For this the EW results have been retabulated, taking the equivalent weight of TNETB in each gas as a standard of comparison:

Explosive	Test Gas	Oxygen Balance	EW_P	EW_I	EW_{IX}
TNETB	N_2	-0.04	1.00	1.00	1.00
RDX		-0.28	0.86	0.84	0.84
TNT		-0.74	0.72	0.70	0.70
TNETB	Air	-0.04	1.00	1.00	1.00
RDX		-0.28	1.05	1.20	1.08
TNT		-0.74	0.88	1.04	0.90
TNETB	O_2	-0.04	1.00	1.00	1.00
RDX		-0.28	1.11	1.28	1.10
TNT		-0.74	0.97	1.18	1.06

From the results presented in this manner, it can be seen that for the explosives fired in nitrogen (i. e., excluding afterburning) the order of blast effectiveness agrees with the order of the oxygen balances. This result might be expected from a qualitative viewpoint, since the more nearly oxygen-balanced explosives would generally develop greater amounts of heat energy in the detonation process. For a more

quantitative analysis it would, of course, be necessary to account for not only the oxygen balance but also the strengths of the chemical bonds existing between the oxygen and the other components of the explosive.

In air and in oxygen, RDX is the most effective of the three. TNT in nitrogen and air is the least effective explosive of the three; in oxygen it attains second place.

This result, that the order of merit of explosives is dependent on the oxygen concentration of the ambient gas, should be of importance in the high altitude application of explosives. It is generally assumed that afterburning ceases at high altitudes; if this is true, then the advantage of using oxygen balanced explosives becomes apparent as a means of obtaining the maximum performance per unit weight of explosive.

It can be shown from the results that the afterburning contribution to the blast energy of TNT fired in air is only a fraction of the total afterburning energy. The heats of combustion for RDX (2% wax) and TNT are 2.3 kcal/gm and 3.5 kcal/gm, respectively. Since both explosives are almost completely oxidized when detonated in air (8) the equivalent weight in air of TNT might be expected to be appreciably greater than that for RDX. That this is not the case indicates that for TNT fired in air the full effect of afterburning is not transmitted to the air blast wave.

In addition to its substantial effect on the air blast performance, the afterburning process also had a marked effect on the position of the secondary shock (Figure 15). For all shots in nitrogen it is seen that the secondary shock occurs far in the negative phase of the shock wave, and approximately the same position for the three test explosives. In the free air series, this shock moved up close to the crossover point for both TNT and RDX, while remaining far in the negative phase for TNETB. In the oxygen series, the secondary shock shifted well into the positive phase for TNT and RDX. It is easily seen that these shifting effects correlate quite well, qualitatively, with the extent of the afterburning contribution to the air shock wave energy.

An explanation has been advanced for this correlation using the generally accepted theory for the formation of the secondary shock

wave. This theory states that the secondary shock wave originates at the charge center as a point reflection of the inward flowing wave which forms at the charge surface. On this basis, the secondary shock must pass through both the explosive gas ball and the surrounding gas, and, assuming a general temperature increase with afterburning, the speed of the secondary shock would increase, permitting the shock to advance on the main shock. Based on this reasoning it seems feasible that a method might be developed for determining the extent of afterburning in any explosion process by measuring the shift of the secondary shock.

Obviously, the shifting of the secondary shock had a strong effect on the positive impulse (see Table V). In the nitrogen shots, the secondary shock was too far in the negative phase to contribute to the positive impulse; in free air, this shock contributed to the positive impulse for both RDX and TNT. In oxygen, an even greater contribution to the positive impulse was made by the secondary shock for these explosives.

It should be kept in mind here that the performance analyses given above do not imply any change in previously established results for air blast performances. Previously obtained EW data for the test explosives are still valid; it is only the changes in blast effects obtained from changing the ambient gas from air to nitrogen and oxygen that are under investigation here.

Correlation of Equivalent Weight with Heat of Detonation

The equivalent weights obtained in this program were correlated to computed heats of detonation of the test explosives. A number of methods are available for computing these heat values (9); of these, the two most generally used ones are:

Mechanism I: Brinkley-Wilson Mechanism: The available oxygen is used to form $H_2O(g)$, CO, and CO_2 in that order.

Mechanism II: Kistiakowsky-Wilson Mechanism: The available oxygen is used to form CO, $H_2O(g)$, and CO_2 in that order.

In both methods, the heat of formation of the explosive is subtracted from the heat of oxidation and a small correction factor is added to convert to a constant volume condition (at 25°C).

A correlation with experimentally determined values of heats of detonation was not made since no such data exist for TNETB; also, the most reliable experimental data available apply to cased and confined explosive charges (10) in contrast to the uncased and unconfined explosives used in this program.

Table I presents the heat of detonation values using the two mechanisms described above. (It was assumed that the wax in the RDX explosive decomposed without reacting in the detonation process. This assumption is based on the findings of previous studies (11).) Table I also presents the heats of combustion, computed in a similar manner as described above (in the case of RDX the wax is assumed to be fully oxidized). The correlation analysis was performed using the heat values calculated from Mechanisms I and II. This correlation revealed the existence of a remarkably linear relationship between the equivalent weights in nitrogen and the heats of detonation, using Mechanism I. These plots are shown in Figures 16 - 18 for EW_P, EW_I, and EW_{IX}, respectively. The lines shown in these figures are least square fits of the data, assuming a functional relationship of the form:

$$EW = \alpha H_D$$

where:

EW = equivalent weight (EW_P, EW_I or EW_{IX})

α = constant of proportionality

H_D = heat of detonation (Mechanism I)

The use of this particular function automatically introduces the reasonable condition that $EW = 0$ when $H_D = 0$. (The point (0, 0) can

actually be taken as an experimental point, since an evaluation of the air blast performance of an inert "explosive" would yield an equivalent weight value of zero.)

It is seen that the [illegible] values for the nitrogen series fall very close to the lines of regression, with the residuals, which are 0.03 or less, falling within the limits of experimental error for equivalent weight determinations (see Table VI).

On the basis of this correlation, it seems reasonable to hypothesize that the air blast effects of a pure organic explosive, in the absence of afterburning, is directly proportional to the heat of detonation, using Mechanism I. Accepting such a hypothesis, it becomes an easy matter to determine equivalent weights for any pure organic explosive (excluding afterburning) simply by calculating its heat of detonation (Mechanism I) and applying the equations given on Figures 16, 17 and 18. Correction factors, involving the explosive oxygen balance, and probably heat of detonation and combustion, would then be needed to account for afterburning contributions. An analysis of these factors is presented in Appendix A.

IV. CONCLUSIONS

Afterburning can contribute substantially to the blast wave energy of organic chemical explosives. The contribution depends in part on the oxygen deficiency of the explosive, increasing, up to a point, as the deficiency increases. The contribution also depends on the oxygen concentration in the ambient gas. As a result of this latter dependency, the order of merit of explosive performance will vary depending upon the oxygen concentration in the ambient gas.

The air blast performances of the test explosives in the absence of afterburning are directly proportional to calculated values of their heats of detonation.

V. FUTURE WORK

Several experimental programs have been planned. One, designed to determine the afterburning effects for aluminized explosives, is

presently in progress. Other programs will evaluate the afterburning contributions resulting from:

1. Variations in charge weight (afterburning scaling law)
2. Increases in turbulence of detonation products.
3. Variations in charge shape
4. Addition of charge casing

To supplement these experimental programs, theoretical studies are being planned based on the analytic methods developed by Kirkwood and Brinkley (13). Also, the method of solution of the basic hydrodynamic equations, as developed by Von Neumann and Richtmeyer (14), will be used to study the relationships existing between the basic explosive parameters and air blast effects.

VI. APPENDIX A

Correlation of Equivalent Weight with Oxygen Balance

The analysis of Section III provided a method for determining the air blast equivalent weight of an explosive by calculating the heat of detonation of the explosive material; however, the equivalent weight so determined is one exclusive of any afterburning contribution. In this section, an attempt will be made to take this factor into account so that the method can be applied to explosives fired in air or other media containing oxygen. In order to do this, correlations will be made using the three pertinent parameters for which data are available: explosive oxygen balance, oxygen concentration in the ambient gas, and increase in equivalent weight ($EW-EW_{N_2}$). These experimental data are tabulated in the following table:

Increase in EW due to afterburning:

$$\Delta EW = EW-EW_{N_2}$$

Explosive	Oxygen Balance	ΔEW_P		ΔEW_I		ΔEW_{IX}	
		Air	Oxygen	Air	Oxygen	Air	Oxygen
TNETB	-0.04	0.02	ND	0.03	ND	0.03	ND
RDX	-0.28	0.21	0.27	0.40	0.67	0.27	0.35
TNT	-0.74	0.18	0.27	0.37	0.69	0.23	0.45

This data can also be tabulated in terms of the relative increase in equivalent weight $(EW-EW_{N_2})/EW_{N_2}$:

Relative Increase in Equivalent Weight

Explosive	Oxygen Balance	EW_P Basis		EW_I Basis		EW_{IX} Basis	
		Air	Oxygen	Air	Oxygen	Air	Oxygen
TNETB	-0.04	0.02	ND	0.03	ND	0.03	ND
RDX	-0.28	0.24	0.31	0.48	0.80	0.32	0.42
TNT	-0.74	0.25	0.37	0.53	0.99	0.33	0.64

Plotting these equivalent weight results against both the oxygen balances and oxygen concentrations revealed no simple or direct correlation, and since only three data points were available, it was not feasible to develop a functional relationship for the data. However, it was possible to make an assumption about the afterburning process which provided at least a semi-quantitative relationship for the afterburning effect.

This assumption was to extend the hypothesis developed in the preceding section as follows: The equivalent weight of an explosive fired in an oxygen bearing gas will be proportional to the sum of the heat of detonation (H_D) and the heat energy contributed from the afterburning process (H_A), using calculated values for H_D and H_A obtained from the arbitrary water decomposition mechanism.*

The equations for equivalent weight then become:

$$\left.\begin{aligned} EW_P &= 0.71\left[H_D + H_A\right] \\ EW_I &= 0.70\left[H_D + H_A\right] \\ EW_{IX} &= 0.70\left[H_D + H_A\right] \end{aligned}\right\} \quad H_2O(g),\ CO,\ CO_2 \text{ Mechanism (Mechanism I)}$$

* This hypothesis, in effect, constitutes a definition of the heat energy contribution obtained from afterburning.

Now, by calculating E_D and experimentally determining equivalent weights, it becomes possible to calculate values of E_A. Using these E_A values and applying Mechanism I, it is possible to determine the amounts of ambient oxygen, ΔO, obtained from the atmosphere. This procedure was followed using the data obtained in this program. The results are tabulated in Table VII and plotted in Figure 19. It can be seen from Figure 19 that the calculated amounts of oxygen obtained from the atmosphere form a somewhat linear relationship with the oxygen balance of the explosives. Such a relationship appears to be quite reasonable from a physical point of view---that is, that the more deficient an explosive is in oxygen, the greater will its potential be for the utilization of oxygen from the surrounding medium.

It has been shown in preceding sections that the afterburning contribution to the air blast is limited, apparently due to the detachment of the shock wave in an early stage of the afterburning process and a limit probably exists for the maximum amount of oxygen obtainable from the atmosphere. Thus, the linear trend indicated in Figure 19 should level off as the magnitude of the oxygen balance increases; in fact, the data indicate just such a trend, especially for the air series.

The ΔO values (oxygen utilized in the afterburning process) based on EW_I are seen to be quite poorly fitted to a linear relationship. This may be due to the limiting effect noted above (and indicated by the dotted lines in Figure 19), or, more likely, may be due to the introduction of the secondary shock into the analysis, this shock being in itself functionally related to afterburning. Because of this added complication no further analysis will be made in this report of the ΔO data based on the EW_I results.

The data presented in Figure 19 (except the data based on EW_I) were fitted assuming a direct proportionality between the variables ΔO and O. B. (oxygen balance). The maximum residuals obtained for ΔO were 0.01 for TNETB and RDX and 0.03 for TNT. These residuals expressed in terms of equivalent weight were less than 0.04.

It is of interest to use the relationships shown in Figure 19 to calculate the total amounts of oxygen utilized by the test explosives. These values can be determined as follows:

$\Delta O_{total} = (\Delta O).W$, where W is the charge weight in grams and ΔO is from the fitted curve

The results are given below:

Total Amount of Oxygen (Gms.) Utilized from Atmosphere

Explosive	Air		Oxygen	
	ΔO_P	ΔO_{IX}	ΔO_P	ΔO_{IX}
TNETB	4.0	5.2	ND	ND
RDX/Wax	28.0	36.0	40.0	50.0
TNT	69.0	89.0	98.0	124.0

The maximum amount of oxygen used in the TNT air series, 89.0 grams, corresponds to a spherical volume of air having a radius of 1.4 feet. For the TNT oxygen series, the maximum amount of oxygen, 124.0 grams, corresponds to a spherical volume of oxygen with a radius of 0.9 feet. It is of interest to note that these radii are in the range of values where the afterburning ceased in the TNT nitrogen experiments (0.75 to 1.5 feet).

The question arises whether the magnitudes of the increases in equivalent weights due to afterburning (and, also, the ΔO values) are dependent on the charge weight. No definite answer can be given to this question at present; however, it does seem unlikely that any large dependence exists. Variations in the afterburning contribution to blast performance due to variations in charge weight should be revealed when the blast performances of different weights of an explosive are scaled (using cube root weight scaling); since the scaling of the blast performance of TNT fired in air, over a large range of charge weights, reveals no such variation it is presumed that the afterburning contributions, per unit weight of charge, are more or less independent of charge weight.

VII. APPENDIX B

Analytic Method for Calculating the Air Blast Performance in Terms of Equivalent Weight

From the findings of the preceding sections, an analytic method can be presented for the determination of the equivalent weight of any pure organic explosive. This method is based on the following analytic expression relating the equivalent weight of an explosive to its heat of detonation and the heat energy added from afterburning:

$$EW = \alpha\left[H_D + H_A\right]$$

where

EW = Equivalent weight of explosive, relative to TNETB fired in nitrogen

H_D = Heat of detonation of explosive (kcal/gm of explosive)

H_A = Heat energy added from afterburning (kcal/gm of explosive)

$$\alpha = \begin{cases} 0.71 \text{ (used when determining } EW_P) \\ 0.70 \text{ (used when determining } EW_{IX}) \end{cases}$$

The first step of the method is a determination of the heat of detonation of the explosive, using the arbitrary water decomposition mechanism (order of products being taken as $H_2O(g)$, CO, CO_2).

The second step is a determination of the ambient oxygen utilized in the afterburning process (ΔO). This can be calculated as follows:

$$\Delta O = \beta\ (-O.\ B.)$$

where

ΔO - Ambient oxygen utilized in afterburning (gm of oxygen/gm of explosive)

O. B. - Oxygen balance (gm of oxygen per gm of explosive)

β - Constant (see table below)

The constant β depends on the explosive effect being considered (peak pressure or positive impulse, excluding the secondary shock) and the ambient gas (nitrogen, air, or oxygen). The values of β (Figure 19) are tabulated below:

Test Gas	Pressure Basis	Impulse Basis
Nitrogen	0.00	0.00
Air	0.24	0.31
Oxygen	0.34	0.43

The third step is the determination of the heat energy evolved from afterburning (H_A). This is done by calculating the added heat energy obtained from the reaction of the detonation products with the additional oxygen, ΔO, obtained from the atmosphere. The order of reaction products for this process is taken to be the same as the order used above in calculating H_D ($H_2O(g)$, CO, CO_2).

Upon obtaining H_D and H_A, the equivalent can be obtained directly from the basic equation:

$$EW = \alpha\left[H_D + H_A\right].$$

As an example and a check of the method described above, an evaluation was made of the explosives tested in this program. Table I, listing explosive properties, was used for obtaining values of H_D and O. B.

Pressure Basis

Explosive/ Test Gas	O. B.	ΔQ	H_A	H_D+H_A	EW (Calculated)	EW (Experimental)
TNETB/N_2	-0.04	0.000	0.000	1.446	1.03	1.00
TNETB/Air		0.010	0.042	1.488	1.06	1.02
TNETB/O_2		0.014	0.059	1.505	1.07	ND
RDX/N_2	-0.28	0.000	0.000	1.195	0.85	0.86
RDX/Air		0.067	0.268	1.463	1.04	1.07
RDX/O_2		0.095	0.378	1.573	1.12	1.13
TNT/N_2	-0.74	0.000	0.000	0.984	0.70	0.72
TNT/Air		0.178	0.299	1.283	0.91	0.90
TNT/O_2		0.252	0.435	1.419	1.01	0.99

Impulse Basis (Excluding Secondary Shock)

Explosive/ Test Gas	O. B.	ΔQ	H_A	H_D+H_A	EW (Calculated)	EW (Experimental)
TNETB/N_2	-0.04	0.000	0.000	1.446	1.01	1.00
TNETB/Air		0.012	0.051	1.497	1.05	1.03
TNETB/O_2		0.017	0.072	1.518	1.06	ND
RDX/N_2	-0.28	0.000	0.000	1.195	0.84	0.84
RDX/Air		0.087	0.347	1.542	1.08	1.11
RDX/O_2		0.120	0.478	1.673	1.17	1.19
TNT/N_2	-0.74	0.000	0.000	0.984	0.69	0.70
TNT/Air		0.229	0.387	1.371	0.96	0.93
TNT/O_2		0.318	0.715	1.699	1.19	1.15

Note that the calculated EW results fall within $\pm$ 4% of the experimentally determined results.

As an additional check on the usefulness of the proposed method, calculations were made of the equivalent weights of Explosive D ($C_6H_6N_4O_7$) and Pentolite (PETN/TNT, 50/50). The results of these calculations were found to be in reasonably close agreement with the experimentally determined equivalent weights for these explosives. The results are given below:

Explosive (fired in air)	E_D kcal/gm	O. B.	Calculated Value[3]	Experimental Value and Standard Error[3,4]
Explosive D[1]	0.76	-0.52	BW_P = 0.69	BW_P = 0.76 ± 0.04
Explosive D[1]	0.76	-0.52	BW_{IX} = 0.78	BW_{IX}[1] = 0.84 ± 0.08
Pentolite[2]	1.20	-0.42	BW_P = 1.00	BW_P = 1.01 ± 0.03

Notes:

1. Experimental and chemical data are from reference (12), except BW_{IX}, which was obtained from unreported data obtained in firing program of 1 lb cast spheres (NOL).

2. Chemical data are from reference (12); experimental value is from this program. The two components, PETN and TNT, are assumed to react independently of each other.

3. Reference explosive is TNETB fired in N_2.

4. Estimated values of standard errors.

In the analysis of the equivalent weight of Pentolite, it was found that the total heat evolution was equal to 1.40 kcal/gm. This value is almost equal to the value of the air blast energy obtained at the charge surface for Pentolite (1.45 kcal/gm) as determined by Kirkwood and Brinkley in their theoretical analysis of air blast waves (13). Although no explicit accounting was made in that analysis of the afterburning effect, several experimental peak pressure values close in to the charge were used (to determine constants of integration) and it is presumed that these data implicitly introduced the effects of afterburning into the analysis.

It should be quite apparent from the discussion in the preceding sections that the analytic method presented herein is rather crude, particularly in regard to the correction term accounting for the afterburning effect. However, in the absence of other suitable analytical methods of this type, it is considered to have utility, at least in practical evaluations of explosive effects. It is also hoped that the

method will provide some insight into the basic mechanisms controlling explosive effects.

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TABLE I

EXPLOSIVE PROPERTIES

Explosive	Composition	Molecular Weight	Oxygen Balance (to CO_2)	Heat of formation per mole	Heat of Detonation I Kcal/gm	Heat of Detonation II Kcal/gm	Heat of Combustion Kcal/gm
TNETB	$C_6H_6N_6O_{14}$	386.2	-0.04	+ 118.6	1.446	1.446	1.620
RDX/Wax	98/2	--	-0.28	--	1.195	1.195	2.310
TNT	$C_7H_5N_3O_6$	227.1	-0.74	+17.8	0.984	0.645	3.490
RDX	$C_3H_6N_6O_6$	222.1	-0.22	-14.7	1.228	1.228	2.140
Wax	CH_2 (Chain)	14	-3.4	+ 5.5	-0.4	-0.4	10.5

Wax assumed to decompose but not react in detonation process.

Wax assumed to oxidize in combustion process.

Heats of Detonation:

I: $H_2O(g)$, CO, CO_2 in that order

II: CO, $H_2O(g)$, CO_2 in that order

TABLE II

PEAK PRESSURE RESULTS

Notes common to all explosive mixtures in this table:

1. Pressures are in psi.
2. $\bar{P}$ = Mean Overpressure.
3. λ = Reduced Distance $d/W^{1/3}$ $(ft/lb^{1/3})$.
4. $\% \sigma_p$ = Standard Deviation in Per Cent.
5. $\% \sigma_{\bar{p}}$ = Standard Error in Per Cent.
6. * = Indicates datum discarded in accordance with Chauvenet's Criterion.

TABLE II, Cont'd

Peak Pressure-Pentolite in Free Air

Shot # \ R	5.61	6.59	7.57	8.80	10.53	12.7λ	15.9λ	20.36
9W0 1	25.60	16.66	12.5λ	9.62	6.53	4.98	3.61	2.35
2	*30.22	17.3λ	13.7λ	9.44	7.38	5.15	3.61	2.42
3	26.63	17.70	13.06	9.62	7.39	5.15	3.61	2.42
4	26.61	17.00	13.7λ	9.62	7.21	4.98	-	-
7	26.30	17.88	13.75	9.28	7.7λ	5.16	2.92	2.3λ
9	27.41	17.13	13.53	9.9λ	7.02	*4.45	3.43	2.40
$\bar{P}$	26.51	17.28	13.39	9.59	7.21	5.08	3.56	2.39
% σ_p	2.5	2.6	3.7	2.3	5.7	1.9	2.5	1.5
% $\sigma_{\bar{P}}$	1.1	1.1	1.5	0.9	2.3	0.8	1.3	0.7

Peak Pressure-Pentolite in 4.5 Ft Air Balloon

Shot # \ R	5.61	6.59	7.57	8.80	10.53	12.7λ	15.9λ	20.36
9W0 12	23.30	17.09	11.91	8.98	6.90	4.83	3.45	2.07
13	2λ.70	*19.89	10.63	9.26	7.03	4.80	3.43	2.40
14	22.97	16.45	11.66	8.7λ	6.68	4.80	3.43	2.23
15	2λ.71	16.53	11.93	10.7λ	7.33	*5.62	3.58	2.56
16	25.56	17.0λ	11.59	10.05	7.50	5.11	3.58	2.39
17	23.3λ	17.38	12.95	10.56	7.16	5.11	3.58	2.39
$\bar{P}$	2λ.10	16.90	11.78	9.72	7.10	4.93	3.51	2.3λ
% σ_p	4.3	2.3	6.3	8.7	4.2	3.3	2.3	7.3
% $\sigma_{\bar{P}}$	1.8	1.0	2.6	3.5	1.7	1.5	0.9	3.0

TABLE II, Cont'd

Peak Pressure-TNT in 4.5 Ft H_2 Balloon

Shot # \ λ	6.00	7.06	8.11	9.43	11.27	13.64	17.06	21.80
9WO 19	16.48	11.85	8.76	7.21	5.15	3.61	2.40	1.71
24	16.90	11.78	9.56	6.66	4.78	3.58	2.39	1.71
28	17.13	12.80	10.21	6.75	4.84	3.63	*2.94	1.73
35	17.01	11.00	8.76	6.36	4.81	3.61	2.41	1.72
37	16.99	11.84	9.61	6.69	5.15	3.60	2.40	1.72
$\bar{P}$	16.90	11.85	9.38	6.73	4.95	3.61	2.40	1.72
% σ_p	1.5	5.4	6.6	4.5	3.8	0.6	0.1	0.2
% $\sigma_{\bar{P}}$	0.6	2.4	3.0	1.9	1.7	0.2	0.04	0.06

Peak Pressure-TNT in 3.0 Ft H_2 Balloon

Shot # \ λ	6.00	7.05	8.10	9.42	11.26	13.62	17.04	21.78
9WO 22	17.53	11.86	9.63	6.70	5.16	3.61	2.41	1.74
25	16.90	11.78	8.71	7.17	4.78	3.58	2.90	*2.05
27	17.11	12.45	8.82	6.74	5.53	3.63	2.94	1.71
33	*14.62	11.87	8.43	6.72	5.16	3.61	2.92	1.76
34	15.98	12.37	8.76	7.22	5.15	3.61	2.41	1.68
40	17.45	12.66	9.24	*7.87	5.13	3.59	2.91	1.71
$\bar{P}$	16.99	12.17	9.03	6.91	5.15	3.60	2.75	1.72
% σ_p	3.6	3.0	4.9	3.8	4.7	0.5	9.5	1.7
% $\sigma_{\bar{P}}$	1.6	1.2	2.0	1.7	1.9	0.2	4.0	0.8

TABLE II, Cont'd

Peak Pressure-TNT in 1.5 Ft H_2 Balloon

Shot # \ λ	6.00	7.06	8.11	9.42	11.27	13.64	17.06	21.80
9WO 88	17.71	12.85	9.37	7.64	5.56	3.99	2.95	1.74
89	17.72	13.90	9.73	7.30	5.56	4.00	2.95	1.74
92	18.53	13.86	9.70	7.27	5.54	4.33	*2.42	1.73
95	18.38	13.36	9.62	7.22	5.15	3.95	2.92	1.72
97	20.26	13.22	10.47	7.90	5.49	3.95	2.92	1.72
98	20.44	13.74	10.48	7.90	6.01	3.95	*3.26	1.72
$\bar{P}$	18.84	13.49	9.90	7.54	5.55	4.03	2.94	1.73
% σ_P	6.4	3.1	4.7	4.2	4.9	3.7	0.6	0.6
% $\sigma_{\bar{P}}$	2.6	1.3	1.9	1.7	2.0	1.5	0.4	0.3

Peak Pressure-TNT Free Air

Shot # \ λ	6.00	7.06	8.11	9.43	11.27	13.64	17.06	21.80
9WO 20	18.38	14.60	10.48	7.90	5.50	3.95	2.92	2.06
21	-	15.14	10.49	7.57	7.05	4.30	2.92	2.06
36	19.38	14.58	*9.60	7.20	5.15	3.94	2.92	2.06
38	18.84	13.70	*10.11	7.54	6.00	4.28	2.91	2.06
39	18.32	14.04	10.44	7.88	5.99	3.94	2.91	2.05
41	18.82	14.54	10.44	8.38	-	-	2.91	2.05
$\bar{P}$	18.75	14.43	10.46	7.75	5.94	4.08	2.92	2.06
% σ_P	2.3	3.5	0.3	5.2	12.12	4.7	0.2	0.2
% $\sigma_{\bar{P}}$	1.2	1.4	0.1	2.1	5.4	2.1	0.1	0.1

TABLE II, Cont'd

Peak Pressure-TNT in 4.5 Ft O_2 Balloon

Shot # \ λ	6.00	7.06	8.11	9.43	11.27	13.64	17.06	21.80
GWO 54	20.24	14.79	10.96	8.24	6.26	4.44	3.25	2.09
55	19.78	14.14	10.96	8.06	5.97	4.13	3.01	2.12
65	21.04	14.43	10.66	7.94	5.91	4.18	3.14	2.17
69	21.59	14.65	11.34	8.13	6.21	4.47	3.01	2.17
85	22.32	*16.25	*12.88	8.35	6.33	4.49	3.12	*2.34
$\bar{P}$	20.99	14.50	10.98	8.14	6.13	4.34	3.11	2.14
% σ_P	4.9	2.0	2.5	1.9	3.0	4.0	3.2	1.8
% $\sigma_{\bar{P}}$	2.2	1.0	1.3	0.9	1.4	1.8	1.4	0.9

Peak Pressure-RIK[1] in 4.5 Ft N_2 Balloon

Shot # \ λ	5.88	6.91	7.94	9.23	11.03	13.35	16.70	21.34
GWO 43	20.66	13.84	10.06	8.57	5.81	4.46	*3.53	*5.69
50	20.00	13.30	9.90	8.55	6.01	4.45	3.09	2.07
51	18.39	13.36	9.48	7.51	5.50	4.14	2.96	2.01
53	22.39	*14.85	10.22	8.09	6.09	4.38	3.16	2.17
63	18.90	13.76	10.12	7.75	6.12	4.17	2.89	1.98
64	19.73	13.44	9.08	7.65	5.47	3.95	3.01	2.12
$\bar{P}$	20.01	13.54	9.81	8.02	5.83	4.26	3.02	2.07
% σ_P	7.1	1.8	4.5	5.7	5.0	4.7	3.5	3.7
% $\sigma_{\bar{P}}$	2.9	0.8	1.8	2.3	2.0	1.9	1.6	1.7

1. 2% wax added

TABLE II, Cont'd

Peak Pressure-RDX[1] Free Air

Shot # / λ	5.88	6.91	7.94	9.23	11.03	13.35	16.70	21.34
GWO 42	23.19	16.09	12.06	9.16	6.54	4.96	3.62	2.22
45	23.33	17.11	11.38	9.30	6.87	4.88	3.41	2.26
46	19.31	16.12	12.43	9.12	6.55	4.87	3.46	2.20
52	19.28	15.68	11.88	9.16	6.87	4.79	3.20	2.33
70	23.67	18.22	12.50	*9.83	6.91	4.91	3.44	2.25
$\bar{P}$	21.76	16.64	12.05	9.18	6.75	4.88	3.43	2.25
% σ_P	10.4	6.2	3.7	0.9	2.7	1.3	4.4	2.1
% $\sigma_{\bar{P}}$	4.6	2.8	1.7	0.4	1.2	0.4	2.0	1.0

Peak Pressure-RDX[1] in 4.5 Ft O_2 Balloon

Shot # / λ	5.88	6.91	7.94	9.23	11.03	13.35	16.70	21.34
GWO 59	22.24	16.03	11.18	9.49	6.80	4.86	3.41	2.34
66	26.26	19.09	14.33	10.24	7.31	4.83	3.54	2.37
67	23.70	16.09	11.91	9.75	7.18	5.24	3.56	*2.52
68	25.44	17.09	12.34	9.86	6.94	4.68	3.62	2.32
86	22.94	15.02	11.31	9.33	6.32	4.39	3.25	2.31
$\bar{P}$	24.12	16.67	12.22	9.73	6.91	4.80	3.48	2.34
% σ_P	7.0	9.3	10.4	3.6	5.6	6.4	4.2	1.1
% $\sigma_{\bar{P}}$	3.1	4.1	4.7	1.6	2.5	2.9	1.7	0.6

1. 2% wax added

TABLE II, Cont'd

Peak Pressure-THETB in 4.5 Ft H_2 Balloon

Shot # \ λ	5.87	6.90	7.93	9.22	11.02	13.34	16.69	21.32
9WO 23	21.73	15.83	11.51	8.50	6.34	4.57	3.33	2.22
32	19.54	16.13	11.57	8.17	6.07	4.61	3.24	2.10
47	28.02	17.07	13.04	9.18	6.92	4.81	3.28	2.22
87	23.69	15.81	10.81	8.32	5.81	4.25	3.00	2.04
$\bar{P}$	23.24	16.21	11.73	8.54	6.28	4.56	3.21	2.14
% σ_P	15.5	3.6	8.0	5.2	7.6	5.1	4.5	4.2
% $\sigma_{\bar{P}}$	7.8	1.8	4.0	2.6	3.8	2.5	2.3	2.1

Peak Pressure-THETB Free Air

Shot # \ λ	5.87	6.90	7.93	9.22	11.02	13.34	16.69	21.32
9WO 29	22.11	15.30	11.25	9.05	6.97	5.08	3.38	2.26
31	-	15.69	11.08	8.57	6.78	4.82	3.37	2.18
44	22.11	16.11	11.40	8.93	6.63	4.74	3.34	2.26
49	19.57	14.29	10.55	8.61	6.33	4.56	*3.13	2.13
$\bar{P}$	21.26	15.35	11.07	8.79	6.68	4.80	3.30	2.21
% σ_P	6.9	5.1	3.3	2.7	4.0	4.5	3.6	2.9
% $\sigma_{\bar{P}}$	4.0	2.5	1.7	1.3	2.0	2.2	1.8	1.4

TABLE II, Cont'd

Peak Pressure-TIMES[1] in 4.5 Ft O_2 Balloon

Shot # \ λ	5.87	6.90	7.93	9.22	11.02	13.34	16.69	21.32
9WO 56	25.19	16.27	12.04	9.14	7.05	4.96	3.54	2.29
58	23.66	16.45	11.50	8.88	7.10	4.79	3.21	2.16
71	19.59	13.69	10.03	7.75	5.64	4.28	2.95	2.05
72	24.18	16.76	12.74	8.89	6.52	4.64	3.31	2.21
74	20.13	14.71	11.05	8.56	6.58	4.65	3.32	2.07
$\bar{P}$	22.55	15.58	11.47	8.64	6.58	4.67	3.27	2.16
% σ_P	11.2	8.5	8.9	6.3	8.9	5.4	6.5	4.7
% $\sigma_{\bar{P}}$	5.0	3.8	4.0	2.8	4.0	2.4	2.9	2.1

1. 2% wax added to all charges in this series

TABLE III

POSITIVE IMPULSE RESULTS (INCLUDING SECONDARY SHOCK)

Notes common to all explosive mixtures in this table:

1. Impulse data are in psi-ms
2. $\bar{I}$ = Mean Positive Impulse (psi-ms)
3. $\bar{i}$ = Mean Reduced Positive Impulse, $I/W^{1/3}$ (psi-ms/lb$^{1/3}$)
4. % $\sigma_{\bar{i}}$ = Standard Deviation in Per Cent
5. % $\sigma_{\bar{i}}$ = Standard Error in Per Cent
6. * Indicates datum discarded in accordance with Chauvenet's Criterion.
7. λ = Reduced Distance $d/W^{1/3}$ (ft/lb$^{1/3}$).

TABLE III (Cont'd)

POSITIVE IMPULSE-PENTOLITE IN FREE AIR

Shot #		7.57	12.7
940	1	8.44	--
	3	7.59	4.95
	4	9.41	4.87
	7	7.50	4.71
	9	8.63	4.17
	$\bar{I}$	8.31	4.67
	$\bar{a}$	8.17	4.59
%	$\sigma_{\bar{a}}$	9.5	7.4
%	$\delta_{\bar{a}}$	4.3	3.7

TABLE III (Cont'd)

POSITIVE IMPULSE-PENTOLITE IN 4.5-Ft AIR BALLOON

Shot #		7.57	12.7
940	12	8.38	4.22
	13	*9.91	4.67
	14	8.34	4.59
	15	8.24	4.63
	16	8.24	4.54
	17	8.47	4.91
	$\bar{I}$	8.33	4.59
	$\bar{a}$	8.19	4.51
%	$\sigma_{\bar{a}}$	3.7	4.9
%	$\delta_{\bar{a}}$	1.6	2.0

TABLE III (Cont'd)

POSITIVE IMPULSE -- TNT IN 4.5-Ft H_2 BALLOON

Shot#	8.10	9.42	11.26	13.62
19	4.70	4.69	4.03	2.82
	5.08	--	3.96	2.87
24	4.19*	4.03*	2.54*	2.50*
	4.63	4.40	3.54	2.80
28	4.99	4.62	3.38	2.71
	5.37	4.79	3.76	3.01
35	4.62	4.65	3.91	2.92
	4.74	4.39	3.35	2.88
37	5.15	4.78	3.97	2.91
	5.11	4.67	--	3.00
$\bar{I}$	4.93	4.62	3.74	2.88
$\bar{R}$	5.19	4.86	3.94	3.03
% σ_R	5.2	3.3	7.4	3.3
% $\sigma_{\bar{R}}$	1.7	1.2	2.6	1.1

TABLE III (Cont'd)

POSITIVE IMPULSE -- TNT IN 3.0-Ft H_2 BALLOON

Shot#	8.10	9.42	11.26	13.62
9W0 22	4.23	4.42	3.95	2.96
	4.65	4.16	3.79	2.87
25	--	4.89	3.65	2.97
	5.19	4.61	--	2.94
27	4.34	4.70	3.51	2.77
	5.09	4.71	3.75	2.84
33	--	4.26	*2.95	2.50
	4.50	4.42	3.43	--
34	4.72	4.29	3.57	2.60
	4.38	4.14	3.91	2.84
40	5.15	5.20	3.89	2.67
	5.45	5.30	4.14	*3.30
$\bar{I}$	4.77	4.59	3.76	2.80
$\bar{R}$	5.02	4.83	3.96	2.95
% σ_R	8.8	8.5	5.8	5.8
% $\sigma_{\bar{R}}$	2.8	2.4	1.8	1.8

TABLE III (Cont'd)

POSITIVE IMPULSE -- TNT IN 1.5-Ft H_2 BALLOON

Shot #	λ	8.11	9.42	11.27	13.64
9M0	88	--	--	5.01	--
		5.47	*6.61	5.29	--
	89	--	5.41	4.63	--
		--	5.37	5.10	3.60
	92	6.37	--	4.24	--
		6.02	5.43	4.25	3.72
	95	5.79	5.39	4.52	3.71
		5.58	5.32	4.70	3.36
	97	5.32	*5.88	4.37	3.41
		5.93	5.49	--	3.49
	98	--	5.40	3.96	3.29
		5.59	5.50	4.48	3.52
	$\bar{I}$	5.76	5.41	4.60	3.51
	$\tilde{I}$	6.05	5.68	4.83	3.69
%	$\sigma_{\bar{I}}$	5.9	1.1	8.5	4.6
%	$\sigma_{\tilde{I}}$	2.1	0.4	2.6	1.6

TABLE III (Cont'd)

POSITIVE IMPULSE-TNT IN FREE AIR

Shot #	λ	8.10	9.42	11.26	13.62
9M0	20	6.91	5.76	4.48	4.04
		6.84	5.95	5.45	3.64
	21	6.35	5.97	4.62	4.02
		7.46	6.08	5.52	4.00
	36	6.56	6.34	4.84	--
		6.06	*5.39	5.16	3.88
	38	7.29	6.34	4.46	--
		6.94	5.71	4.82	3.60
	39	6.78	*4.29	4.48	3.79
		6.83	6.19	4.75	4.03
	41	6.54	6.06	4.53	4.02
		6.53	6.28	5.04	4.13
	$\bar{I}$	6.76	6.07	4.85	3.92
	$\tilde{I}$	7.10	6.37	5.09	4.12
%	$\sigma_{\bar{I}}$	5.6	3.6	7.7	4.6
%	$\sigma_{\tilde{I}}$	1.6	1.1	2.2	1.5

TABLE III (Cont'd)

POSITIVE IMPULSE-TNT IN 4.5-Ft O_2 BALLOON

Shot #	λ	8.10	9.42	11.26	13.62
9W0	54	7.54	7.64	6.75	4.30
		7.66	7.54	6.78	4.60
	55	7.98	6.75	6.29	4.21
		7.72	7.46	--	4.44
	65	8.59	6.45	5.70	*5.04
		7.69	6.35	5.78	4.43
	69	8.29	6.58	6.18	4.71
		--	7.67	5.54	4.52
	$\bar{I}$	7.92	7.06	6.15	4.46
	$\bar{E}$	8.34	7.43	6.48	4.70
%	$\sigma_{\bar{E}}$	4.8	8.1	8.0	3.8
%	$\sigma_{\bar{E}}$	1.8	2.8	3.0	1.4

TABLE III (Cont'd)

POSITIVE IMPULSE-RDX[1] IN 4.5-Ft H_2 BALLOON

Shot #	λ	7.94	9.23	11.03	13.35
9W0	43	6.20	5.27	--	4.01
		5.71	--	4.79	3.67
	50	6.19	5.13	4.88	--
		5.31	5.44	4.65	3.87
	51	6.20	5.31	4.49	3.70
		5.71	5.60	4.54	3.55
	53	5.51	5.23	4.32	3.22
		5.51	5.21	*5.38	3.31
	63	6.52	5.57	4.49	3.53
		5.91	5.31	4.62	3.46
	64	5.73	5.01	4.31	3.55
		5.42	4.96	4.51	3.36
	$\bar{I}$	5.83	5.28	4.56	3.57
	$\bar{E}$	6.01	5.44	4.70	3.66
%	$\sigma_{\bar{E}}$	6.5	3.8	4.0	6.8
%	$\sigma_{\bar{E}}$	1.8	1.1	1.3	2.2

1. 2% wax added

TABLE III (Cont'd)

POSITIVE IMPULSE-RDX[1] (FREE AIR)

Shot #	λ	7.94	9.23	11.03	13.35
940	42	7.94	7.44	6.65	5.17
		8.53	6.83	--	4.55
	45	7.23	6.94	4.89	4.41
		8.15	6.45	5.37	4.72
	46	7.84	7.58	5.52	4.38
		7.78	6.44	5.87	4.06
	52	6.40	6.64	5.62	--
		6.53	7.15	6.28	4.07
	70	7.35	6.68	5.99	4.76
		--	7.94	5.69	4.00
	Ī	7.53	7.01	5.76	4.46
	a	7.76	7.23	5.94	4.60
%	Range	9.5	7.3	8.9	8.7
%	a	3.2	2.4	3.0	2.8

TABLE III (Cont'd)

POSITIVE IMPULSE-RDX[1] IN 4.5-Ft O_2 BALLOON

Shot #	λ	7.94	9.23	11.03	13.35
940	59	8.16	6.46	6.10	5.33
		7.77	7.59	6.33	5.05
	66	9.97	8.10	7.02	5.30
		8.54	--	6.55	4.94
	67	8.86	7.35	6.83	5.87
		7.92	--	6.54	5.52
	68	9.54	7.22	5.94	5.59
		7.78	8.03	6.81	5.32
	Ī	8.57	7.46	6.53	5.36
	a	8.84	7.69	6.73	5.53
%	Range	9.7	8.1	5.8	5.6
%	a	3.4	3.2	2.1	2.0

1. 2% wax added

TABLE III (Cont'd)

POSITIVE IMPULSE-THETB IN 4.5-Ft H_2 BALLOON

Shot # \ λ	7.93	9.22	11.02	13.34
940 23	--	6.26	5.72	4.32
	6.64	--	5.95	3.67
32	6.48	6.04	4.35	3.57
	6.61	5.50	4.51	3.37
47	6.37	6.38	4.73	--
	6.53	--	5.28	4.36
$\bar{I}$	6.53	6.04	5.09	3.86
$\bar{\theta}$	6.73	6.22	5.24	3.98
% $\sigma_{\bar{I}}$	1.6	6.5	13.0	11.7
% $\sigma_{\bar{\theta}}$	.74	3.2	5.3	5.2

TABLE III (Cont'd)

POSITIVE IMPULSE-THETB IN FREE AIR

Shot # \ λ	7.93	9.22	11.02	13.34
29	6.39	6.01	5.91	*5.22
	5.70	5.88	5.87	4.55
31	6.72	5.84	--	--
	5.69	*5.27	--	4.15
44	6.95	6.03	5.17	3.63
	7.08	--	4.92	4.45
49	6.40	6.17	5.07	3.96
	7.29	6.27	5.40	4.22
$\bar{I}$	6.53	6.03	5.39	4.16
$\bar{\theta}$	6.73	6.21	5.55	4.28
% $\sigma_{\bar{I}}$	9.2	2.7	7.7	8.1
% $\sigma_{\bar{\theta}}$	3.2	1.1	3.2	3.3

TABLE III (Cont'd)

POSITIVE IMPULSE-TESTS[1] IN 4.5-Ft O_2 BALLOON

Shot # \ λ	7.93	9.22	11.02	13.34
56	7.90	6.54	6.09	4.85
	6.75	*7.43	5.41	4.99
58	7.88	--	6.42	5.35
	7.22	6.45	5.98	4.59
71	7.37	*5.51	4.58	4.29
	--	--	5.22	4.26
72	7.44	6.14	5.45	4.70
	--	6.45	5.26	3.89
74	7.43	6.63	5.57	4.91
	6.70	6.23	5.89	4.43
$\bar{I}$	7.34	6.41	5.59	4.63
$\bar{s}$	7.56	6.60	5.76	4.77
% $\bar{s}$	6.1	2.9	9.4	9.2
% $\bar{s}$	2.1	1.2	3.0	2.9

[1] 2% wax added to all charges in this series.

TABLE IV

POSITIVE IMPULSE RESULTS (EXCLUDING SECONDARY SHOCK)

Notes common to all explosive mixtures in this table:

See Table III for definition of symbols

See Table III for results for series in 3.0' and 4.5' N_2 Balloons

(Secondary shock does not contribute to positive impulse in these series.)

TABLE IV

POSITIVE IMPULSE-TNT IN 1.5-Pt H_2 BALLOON

(excluding secondary shock)

Shot # \ λ		8.11	9.42	11.27	13.64
9W0	88	--	--	4.83	--
		5.38	*6.22	4.96	--
	89	--	5.35	4.41	--
		--	5.19	4.80	3.54
	92	*6.34	--	4.09	--
		5.71	5.31	4.20	3.58
	95	5.79	5.39	4.46	3.71
		5.51	5.25	4.58	3.36
	97	5.13	*5.68	4.31	3.41
		5.79	5.38	--	3.38
	98	--	5.27	3.96	3.29
		5.59	5.38	4.39	3.51
	$\bar{I}$	5.56	5.32	4.46	3.47
	$\bar{s}$	5.84	5.59	4.68	3.64
%	σ_s	4.3	1.4	7.3	4.1
%	$\sigma_{\bar{s}}$	1.6	0.5	2.2	1.5

TABLE IV (Cont'd)

POSITIVE IMPULSE-TNT IN FREE AIR

(excluding secondary shock)

Shot # \ λ		8.10	9.42	11.26	13.62
9W0	20	6.34	5.57	4.26	3.82
		6.15	5.40	*5.05	3.38
	21	5.99	5.83	4.48	3.85
		6.90	5.74	*5.20	3.71
	36	5.80	5.87	4.36	--
		5.62	5.05	4.59	3.49
	38	6.97	6.00	4.17	--
		6.28	5.18	4.69	3.49
	39	6.28	*3.90	4.30	3.47
		6.32	5.43	4.41	3.59
	41	6.12	5.73	4.07	3.78
		5.94	5.54	4.61	3.71
	$\bar{I}$	6.23	5.58	4.39	3.63
	$\bar{s}$	6.54	5.86	4.61	3.81
%	σ_s	6.4	5.1	4.6	4.7
%	$\sigma_{\bar{s}}$	1.8	1.5	1.4	1.5

TABLE IV (Cont'd)

POSITIVE IMPULSE-TNT IN 4.5-Pt O_2 BALLOON

(excluding secondary shock)

Shot # / Δ		8.11	9.43	11.27	13.64
9W0	54	6.72	6.74	5.54	3.84
		7.16	6.53	6.11	4.14
	55	7.27	6.16	5.64	3.67
		6.70	6.56	--	3.77
	65	7.36	5.61	4.85	4.32
		6.69	5.70	5.08	3.97
	69	7.81	5.89	5.52	4.26
		--	6.97	4.81	4.01
	$\bar{I}$	7.10	6.27	5.36	4.00
	$\bar{a}$	7.46	6.58	5.63	4.20
%	$\sigma_{\bar{a}}$	5.9	7.4	8.7	5.7
%	$\sigma_{\bar{I}}$	2.2	2.6	3.3	2.0

TABLE IV (Cont'd)

POSITIVE IMPULSE-RDX[1] IN FREE AIR

(excluding secondary shock)

Shot # / Δ		7.94	9.23	11.03	13.35
9W0	42	7.54	6.98	6.16	*4.92
		7.98	6.38	--	4.16
	45	6.97	6.58	*4.45	4.26
		7.77	5.90	5.31	4.39
	46	7.62	7.01	5.33	4.07
		7.23	6.35	5.62	3.96
	52	6.06	6.21	5.44	--
		6.16	6.70	5.96	3.89
	70	7.02	6.45	5.58	4.40
		--	7.13	5.24	3.90
	$\bar{I}$	7.15	6.57	5.58	4.13
	$\bar{a}$	7.37	6.77	5.75	4.26
%	$\sigma_{\bar{a}}$	9.5	5.9	5.9	5.2
%	$\sigma_{\bar{I}}$	3.1	1.9	2.1	1.9

1. 2% wax added

TABLE IV (Cont'd)

POSITIVE IMPULSE-PSIX[1] IN 4.5-Ft O_2 BALLOON
(excluding secondary shock)

Shot #	7.95	9.23	11.03	13.35
SWO 59	7.27	6.05	5.30	4.80
	7.07	6.64	5.51	4.54
	*9.08	7.32	6.22	4.72
	7.76	--	5.69	4.27
	7.81	6.66	6.07	4.92
	7.10	--	5.87	5.07
	8.21	6.26	5.50	5.30
	7.05	7.01	5.74	4.44
$\bar{I}$	7.47	6.66	5.74	4.76
$\bar{a}$	7.69	6.86	5.91	4.90
% $\sigma_{\bar{a}}$	6.1	7.0	5.4	7.1
% $\sigma_{\bar{a}}$	2.3	2.9	1.9	2.4

1. 2% wax added

TABLE IV (Cont'd)

POSITIVE IMPULSE-THETB IN FREE AIR

(excluding secondary shock)

Shot #	7.93	9.22	11.02	13.34
SWO 29	6.39	6.01	5.68	4.89
	5.70	5.70	5.51	4.55
31	6.65	5.84	--	--
	5.69	*5.27	--	4.15
44	6.95	6.03	5.17	3.63
	7.08	--	4.92	4.45
49	6.40	5.95	5.07	3.96
	7.10	6.20	5.36	4.18
$\bar{I}$	6.49	5.96	5.28	4.26
$\bar{a}$	6.68	6.14	5.44	4.39
% $\sigma_{\bar{a}}$	8.7	2.9	5.4	9.7
% $\sigma_{\bar{a}}$	3.1	1.2	2.2	3.7

TABLE IV (Cont'd)

POSITIVE IMPULSE-TESTS[1] IN 4.5-Ft O_2 BALLOON
(excluding secondary shock)

Shot # \ Δ	7.93	9.22	11.02	13.34
56	7.67	6.17	*6.01	4.59
	6.52	6.84	5.20	4.84
58	7.04	--	5.69	4.93
	6.79	5.82	5.34	4.28
71	6.91	5.36	*4.41	4.04
	--	--	5.02	3.87
72	7.19	6.14	5.15	4.47
	--	6.12	5.03	3.77
74	7.04	6.29	5.33	4.57
	6.29	5.92	5.49	4.15
$\bar{I}$	6.93	6.08	5.28	4.35
$\bar{a}$	7.14	6.26	5.44	4.48
% δ_a	6.0	6.9	4.4	8.9
% $\delta_{\bar{a}}$	2.1	2.4	1.6	2.9

[1] 2% wax added to all charges in this series.

TABLE V: EQUIVALENT WEIGHT RESULTS

EXPLOSIVE	GAS	EW_P		EW_I		EW_{IX}	
TNETB	N_2	1.00		1.00		1.00[1]	
TNETB	free air	1.02	±.03[2]	1.03	±.06	1.03	±.06
TNETB[3]	O_2	1.02	±.03	1.18	±.07	1.08	±.07
RDX[3]	N_2	0.86	±.02	0.84	±.05	0.84	±.05
RDX[3]	free air	1.07	±.03	1.24	±.09	1.11	±.07
RDX[3]	O_2	1.13	±.03	1.51	±.10	1.19	±.08
TNT	N_2	0.72	±.02	0.70	±.04	0.70	±.04
TNT	free air	0.90	±.01	1.07	±.06	0.93	±.05
TNT	O_2	0.99	±.02	1.39	±.09	1.15	±.08
TNT	N_2 (3.0' diam.)	0.72	--	.69	--	.69	--
TNT	N_2 (1.5 diam.)	0.85	±.02	0.91	±.04	0.88	±.04
PENT.	free air	1.01		--	--	--	--
PENT.	air (4.5' diam.)	.97	±.014[4]	--	--	--	--

1. $EW_{IX} = EW_I$ for N_2 series
2. Precision indices relative to TNETB in N_2
3. 2% wax added
4. Precision index relative to Pentolite in free air

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TABLE VI

EQUIVALENT WEIGHTS (N_2 SERIES), EXPERIMENTAL VS. CALCULATED RESULTS:

		EXPERIMENTAL	CALCULATED	% ERROR
TNETB	EW_P	1.00	1.03	+ 3%
	EW_I	1.00	1.01	+ 1%
	EW_{IX}	1.00	1.01	+ 1%
RDX	EW_P	0.86	0.85	- 1%
	EW_I	0.84	0.84	0%
	EW_{IX}	0.84	0.84	0%
TNT	EW_P	0.72	0.70	- 3%
	EW_I	0.70	0.69	- 1%
	EW_{IX}	0.70	0.69	- 1%
INERT	ALL	0.00	0.00	0%

CALCULATED RESULTS OBTAINED FROM:

$EW_P = 0.71\ H_D$
$EW_I = 0.70\ H_D$
$EW_{IX} = 0.70\ H_D$

} $H_2O(g)$, CO, CO_2 MECHANISM

TABLE VII

HEAT CONTRIBUTION FROM AFTERBURNING AND AMOUNT OF AMBIENT OXYGEN UTILIZED

Explosive	Oxygen Balance	Ambient Gas	Pressure Basis			Impulse Basis			Impulse Basis[2]		
			ΔEW	H_A	ΔO	ΔEW	H_A	ΔO	ΔEW	H_A	ΔO
TNETB	-0.04	N_2	H_A and ΔO Values are Zero Since Fitted Curve Values Were Used ($\Delta EW = 0$)								
RDX[1]	-0.28										
TNT	-0.74										
TNETB	-0.04	Air	-0.01	-0.01	N. D.[3]	0.02	0.03	0.01	0.02	0.03	0.01
RDX[1]	-0.28		0.22	0.31	0.08	0.40	0.57	0.14	0.27	0.39	0.10
TNT	-0.74		0.20	0.28	0.17	0.38	0.54	0.28	0.24	0.34	0.20
TNETB[1]	-0.04	O_2	N. D.	-	-	-	-	-	-	-	-
RDX[1]	-0.28		0.28	0.39	0.10	0.67	0.96	0.24	0.35	0.50	0.12
TNT	-0.74		0.29	0.41	0.24	0.70	1.00	0.39	0.46	0.66	0.31

1. 2% wax added

2. Excluding Secondary Shock

3. Negative values of ΔO not possible; assumed to be zero for simplicity

Notes:

a. $\Delta EW = EW - EW_{N_2}$ (Fitted Curve Values of EW_{N_2}).

b. H_A = Heat Contribution from Afterburning (kcal/gm of explosive):

$H_A = \Delta EW/0.71$ (Pressure Basis)

$= \Delta EW/0.70$ (Impulse Basis)

c. ΔO = Amount of Ambient Oxygen Utilized, Mechanism I. (gms oxygen/gm of explosive)

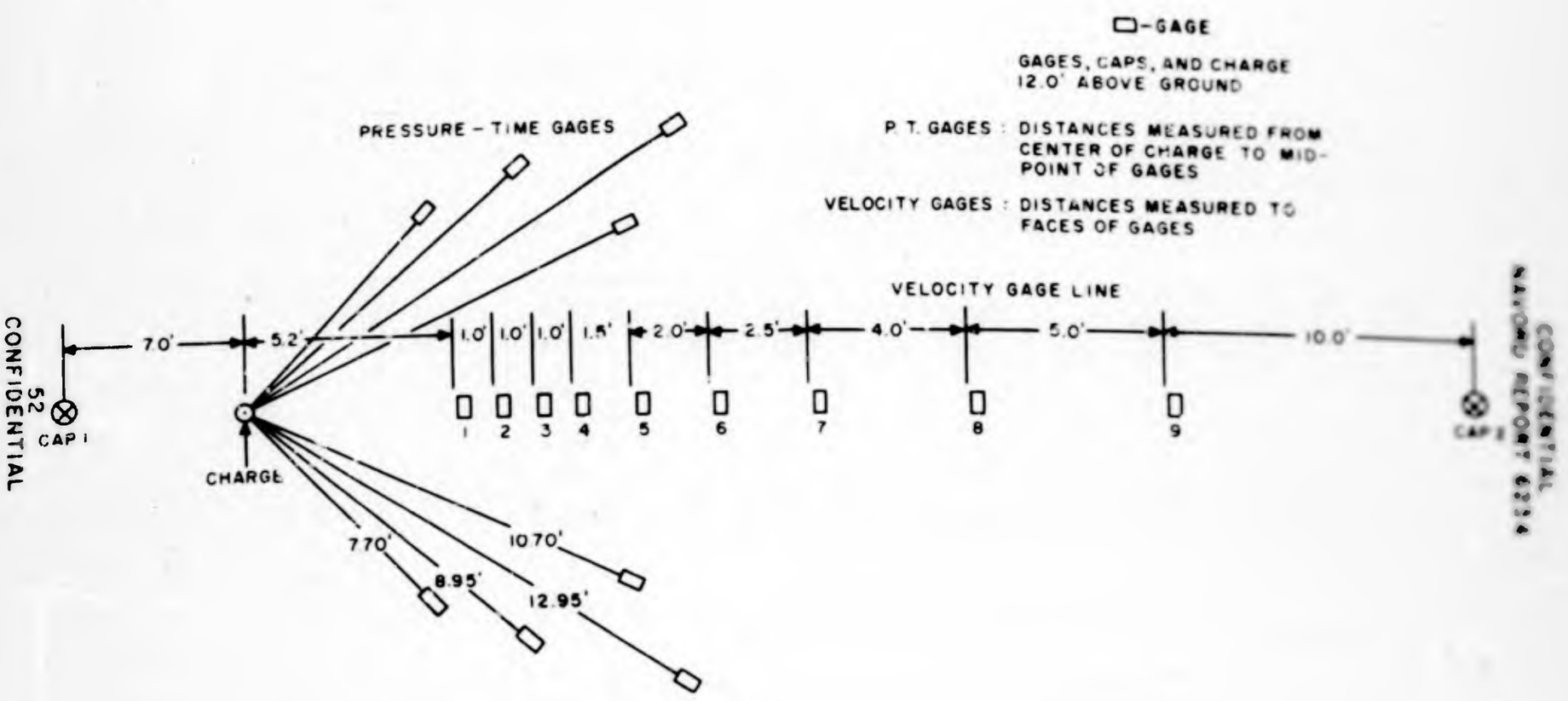
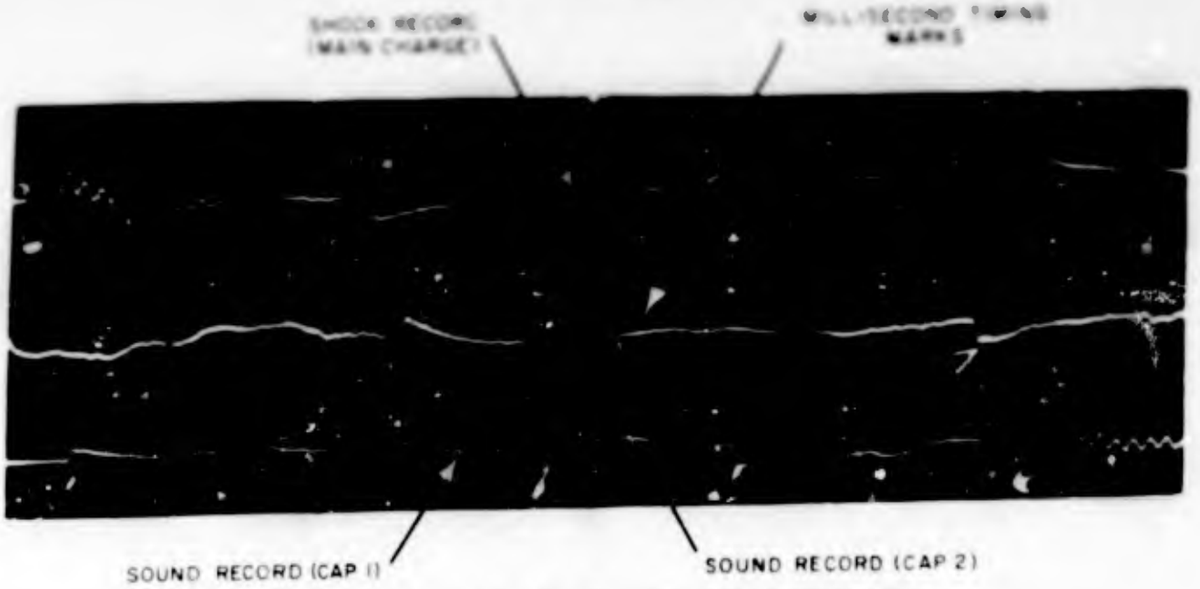
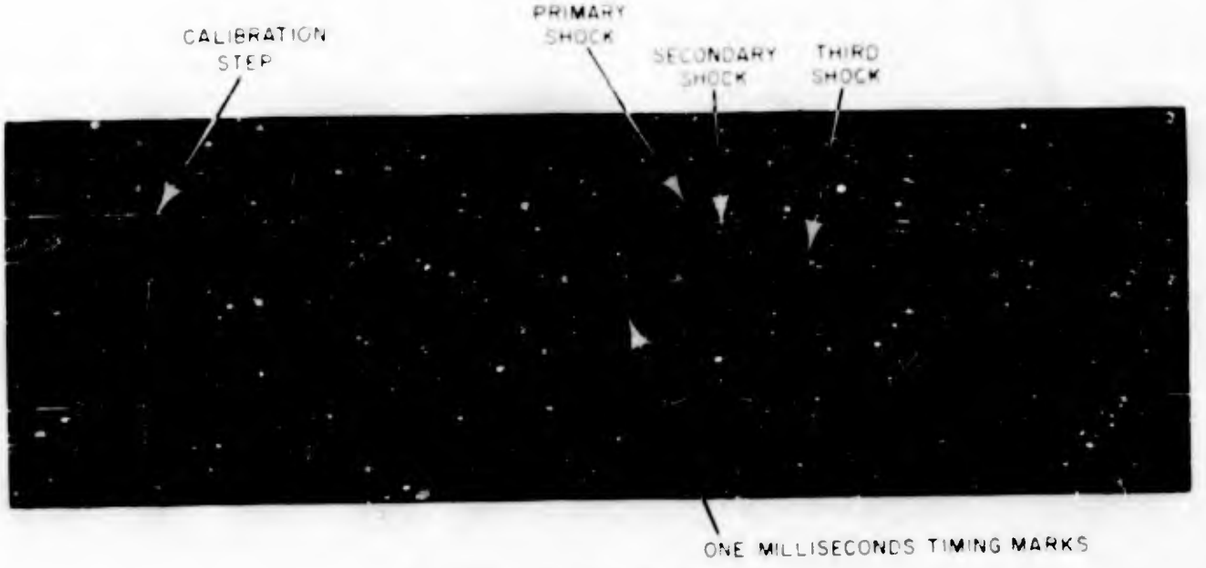


FIG. 1 PLAN VIEW OF EXPERIMENTAL SET-UP



NUMBERS CORRESPOND TO VELOCITY GAGE NUMBERS ON FIGURE 1 OF THIS REPORT

A PORTION OF A VELOCITY RECORD



PRESSURE – TIME RECORD

CHARGE COMPOSITION TNT
AMBIENT GAS OXYGEN, IN 4 1/2 FT DIAM BALLOON
CHARGE WGT 0 85 LB
PEAK PRESSURE 8 06 PSI
POSITIVE IMPULSE 6 75 PSI-MS
DISTANCE FROM CHARGE 8 95'

FIG. 2 TYPICAL RECORDS

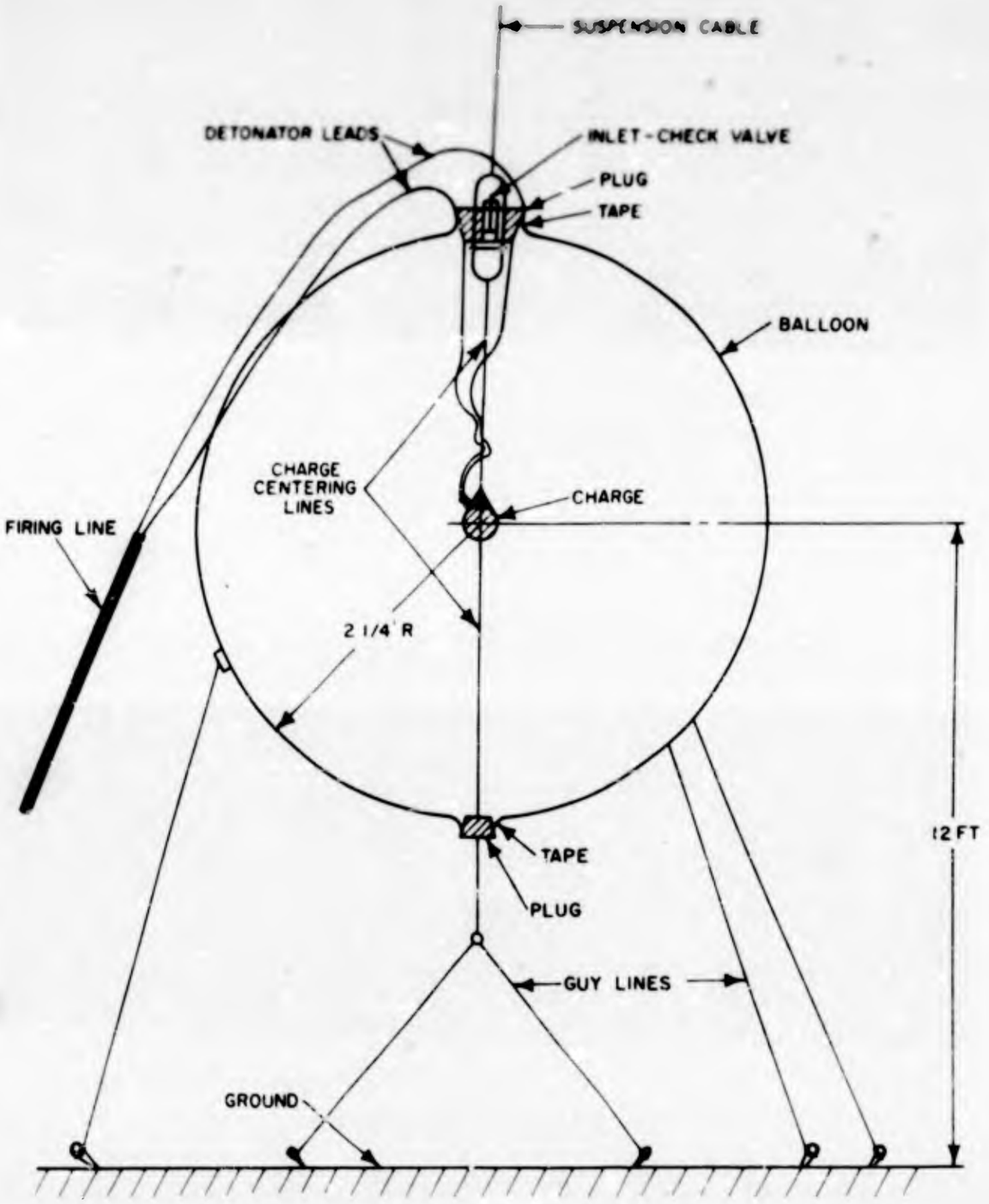


FIG. 3 CHARGE SUSPENSION USING BALLOON (SECTION VIEW)

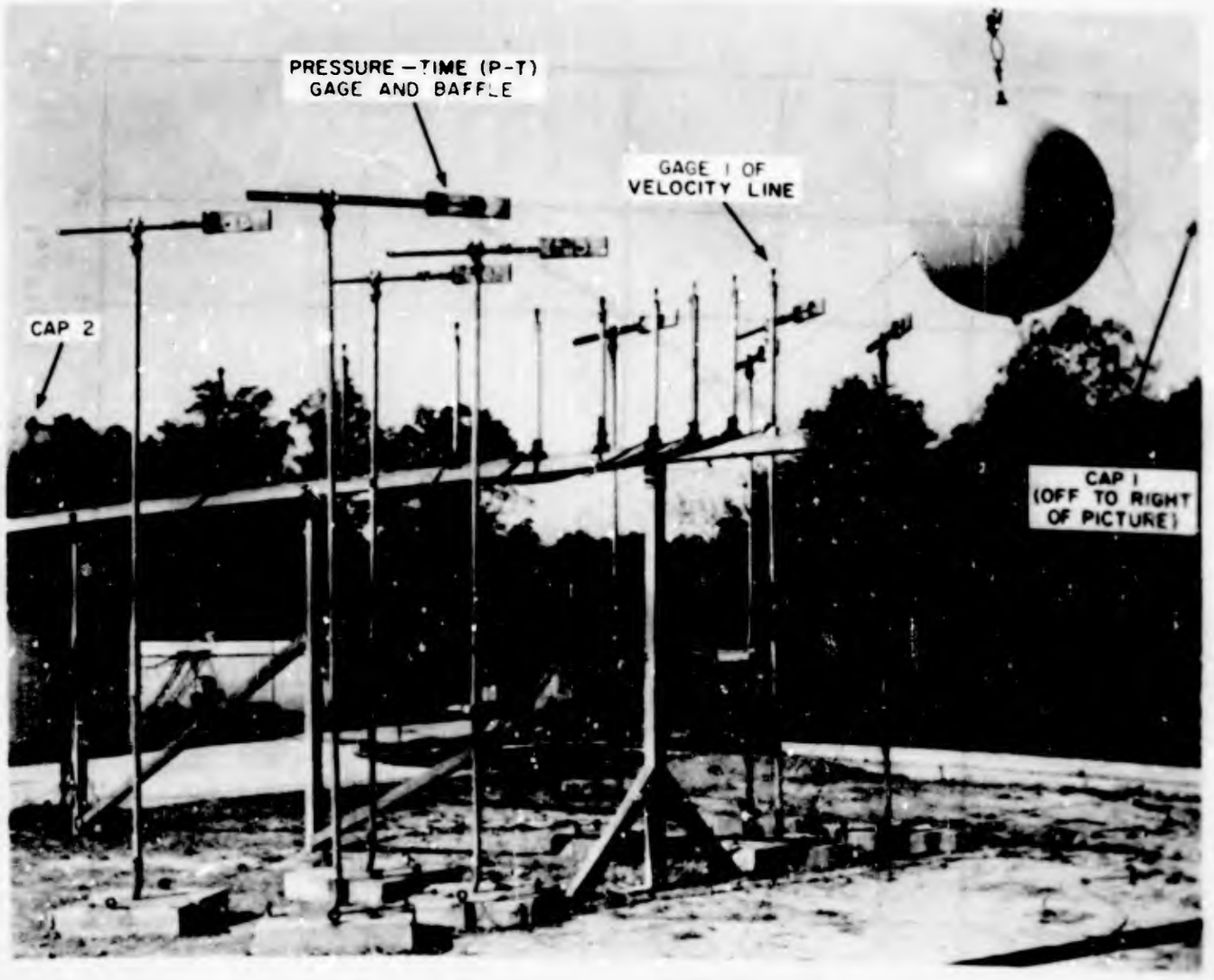


FIG 4 TYPICAL FIELD ARRANGEMENT FOR BALLOON SHOT

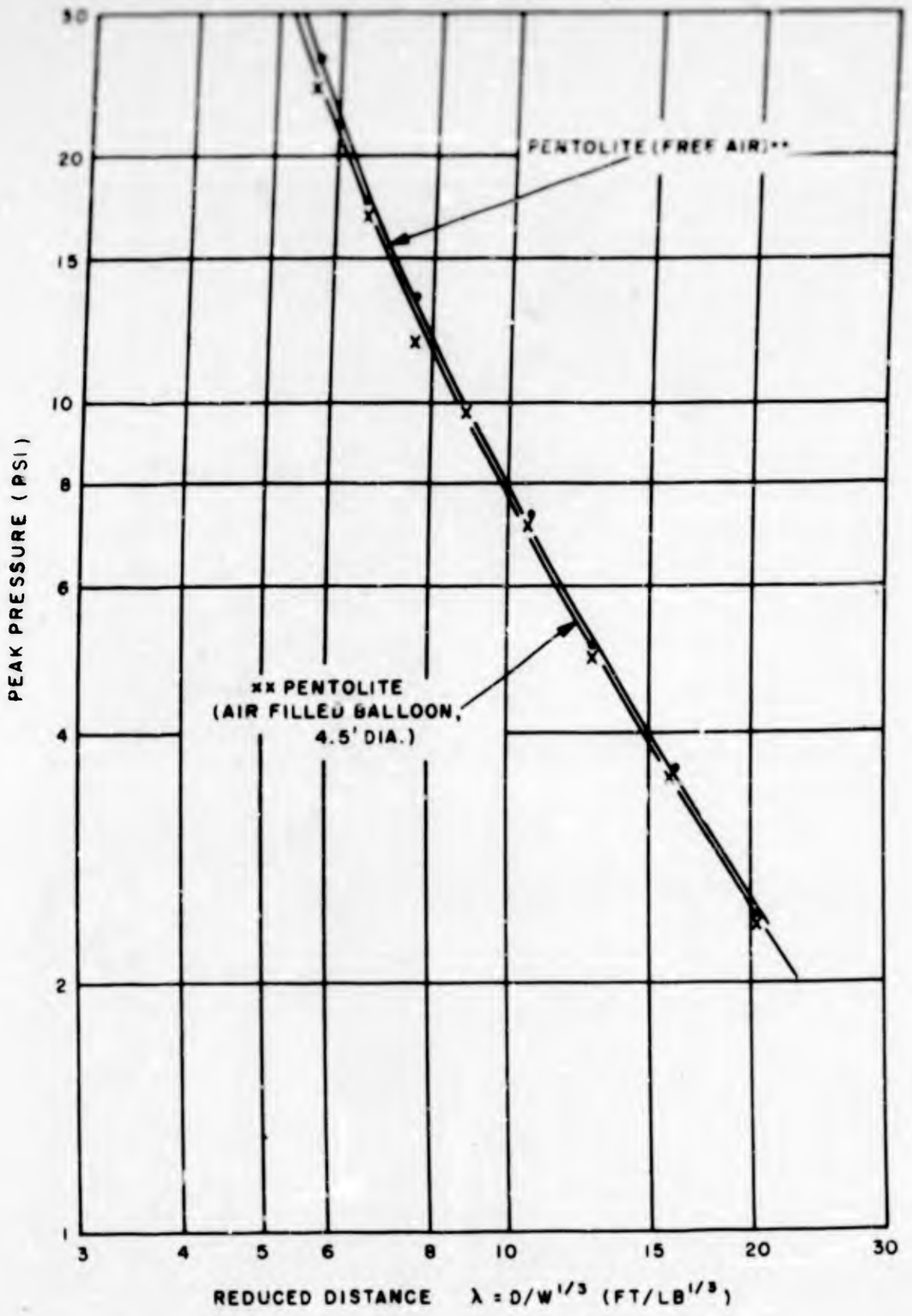


FIG. 5 COMPARISON OF PEAK PRESSURE VS REDUCED DISTANCE FOR CHARGES FIRED IN AIR WITH AND WITHOUT A BALLOON

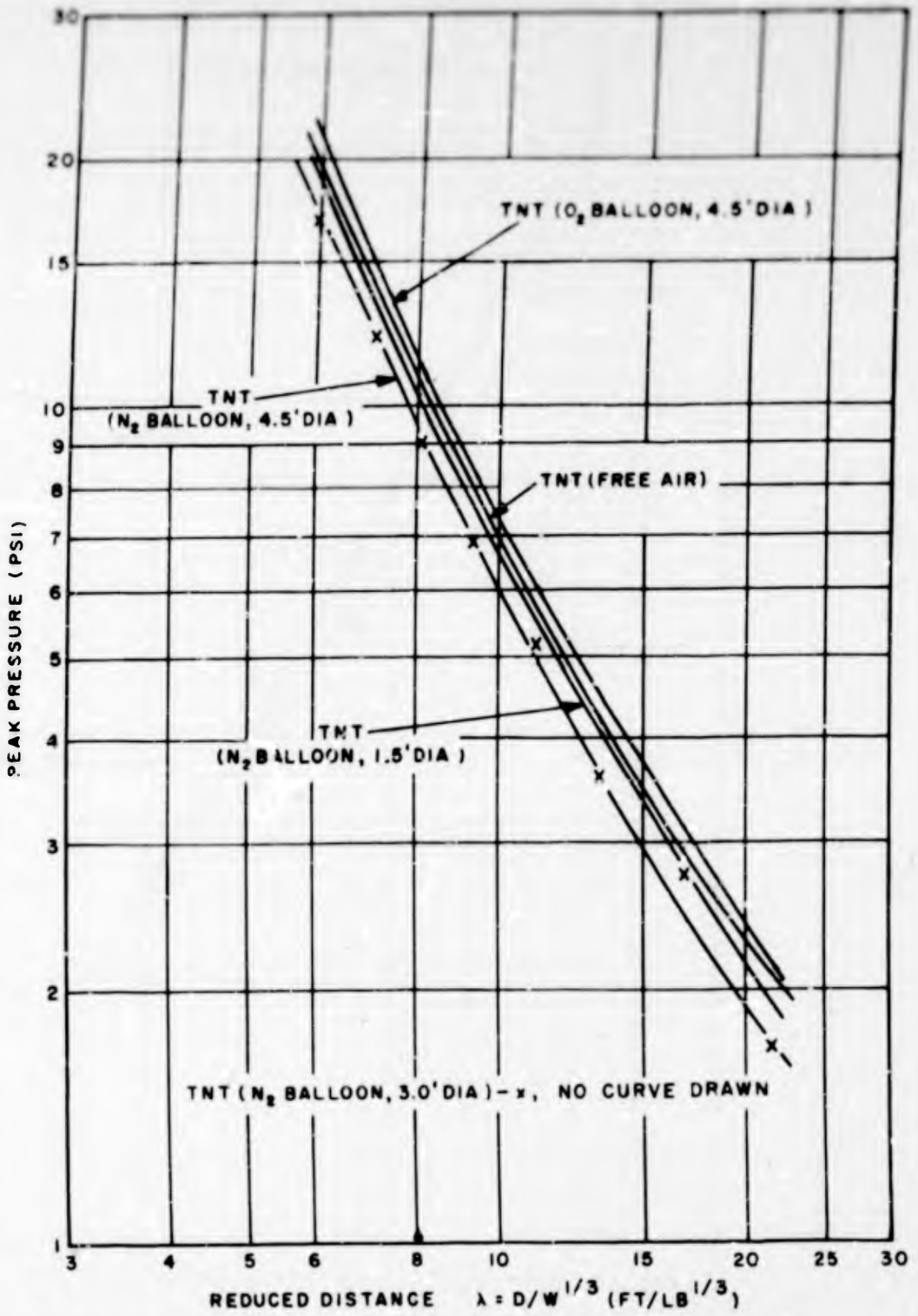


FIG. 6 PEAK PRESSURE VS REDUCED DISTANCE AS A FUNCTION OF BOTH OXYGEN CONCENTRATION IN TEST GAS AND BALLOON SIZE: TNT RESULTS

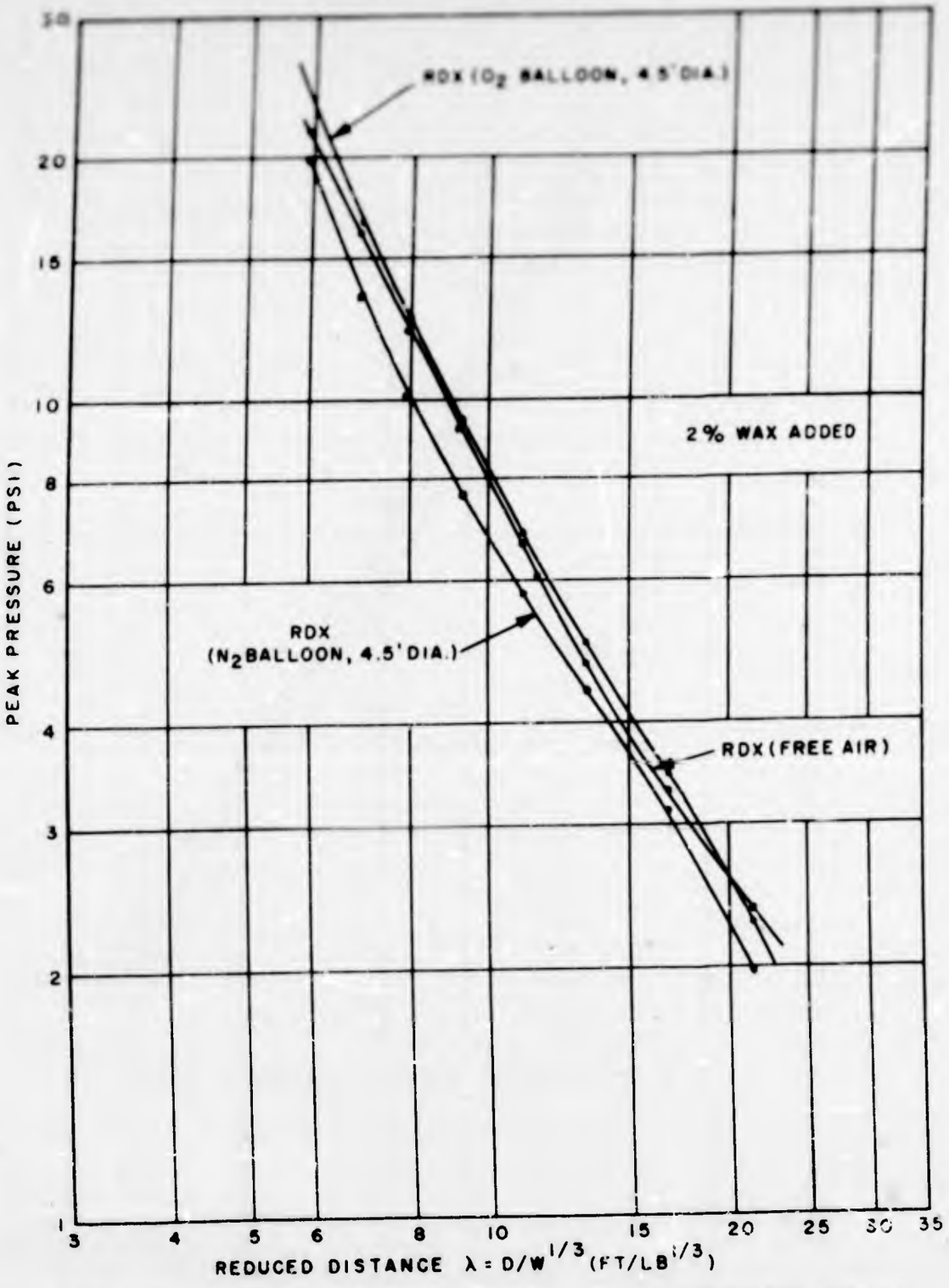


FIG. 7 PEAK PRESSURE VS REDUCED DISTANCE AS A FUNCTION OF OXYGEN CONCENTRATION IN TEST GAS: RDX RESULTS

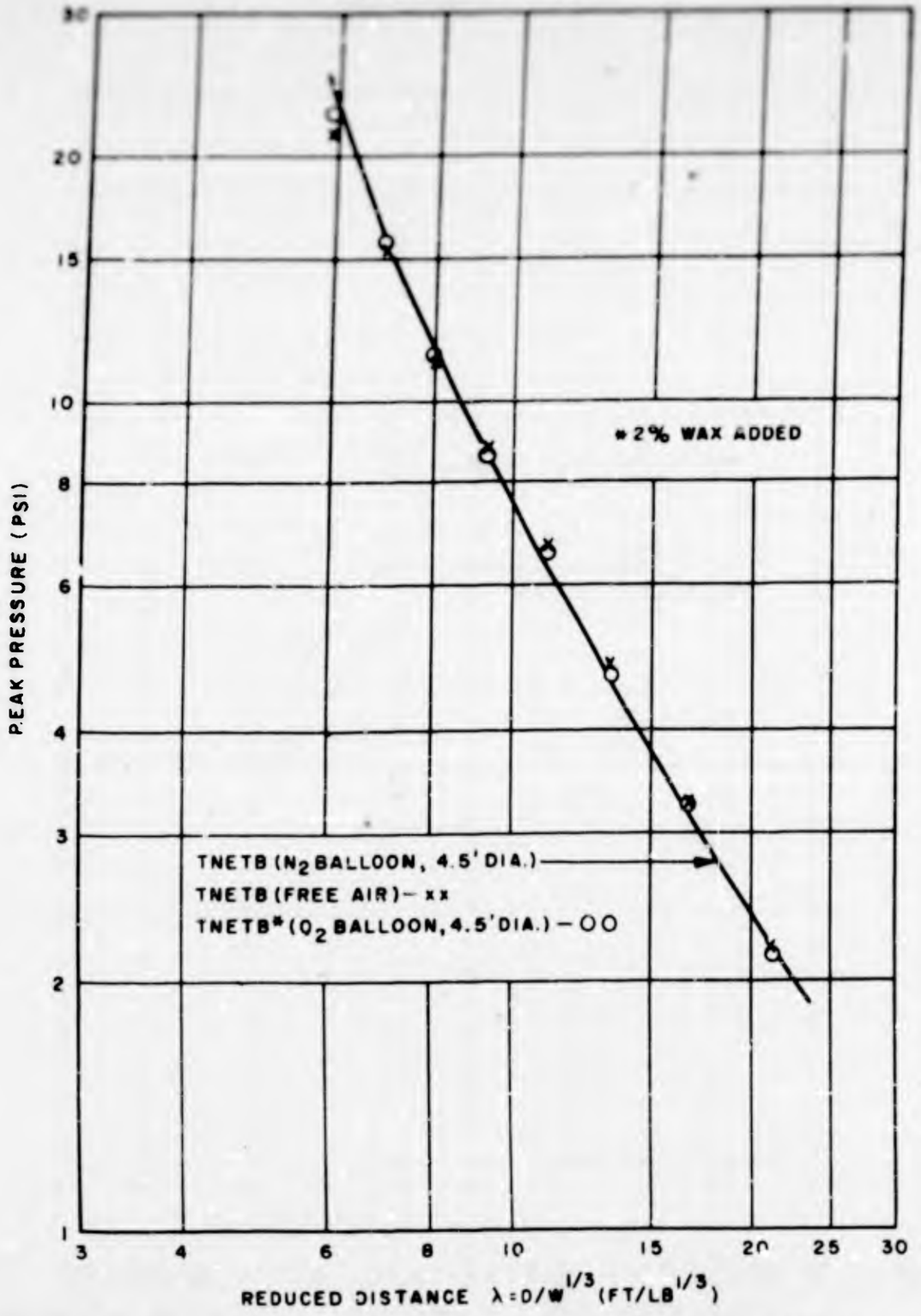


FIG. 8 PEAK PRESSURE VS REDUCED DISTANCE AS A FUNCTION OF OXYGEN CONCENTRATION IN TEST GAS: TNETB RESULTS

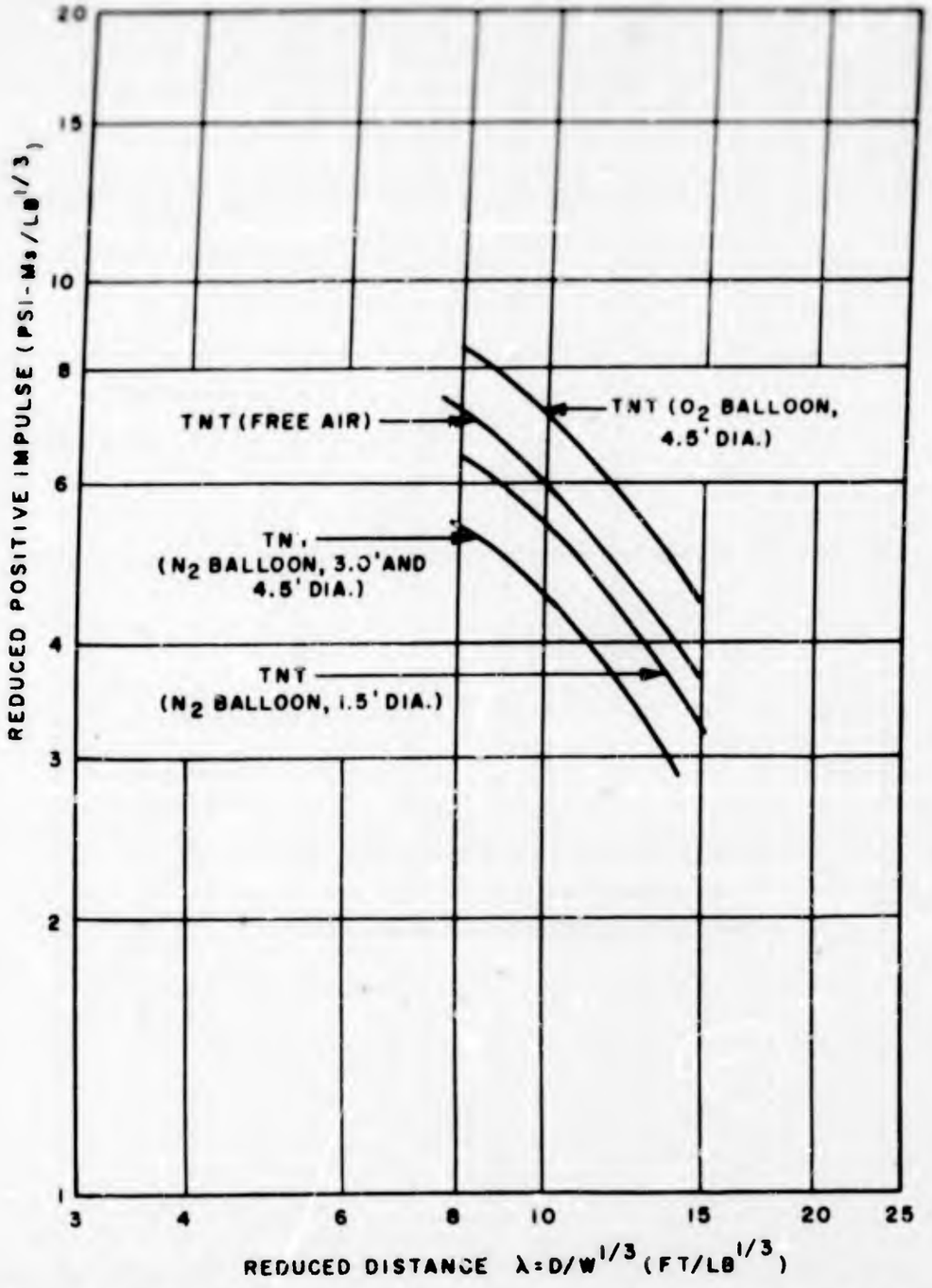


FIG. 9 REDUCED POSITIVE IMPULSE VS REDUCED DISTANCE AS A FUNCTION OF BOTH OXYGEN CONCENTRATION IN TEST GAS AND BALLOON SIZE: TNT RESULTS

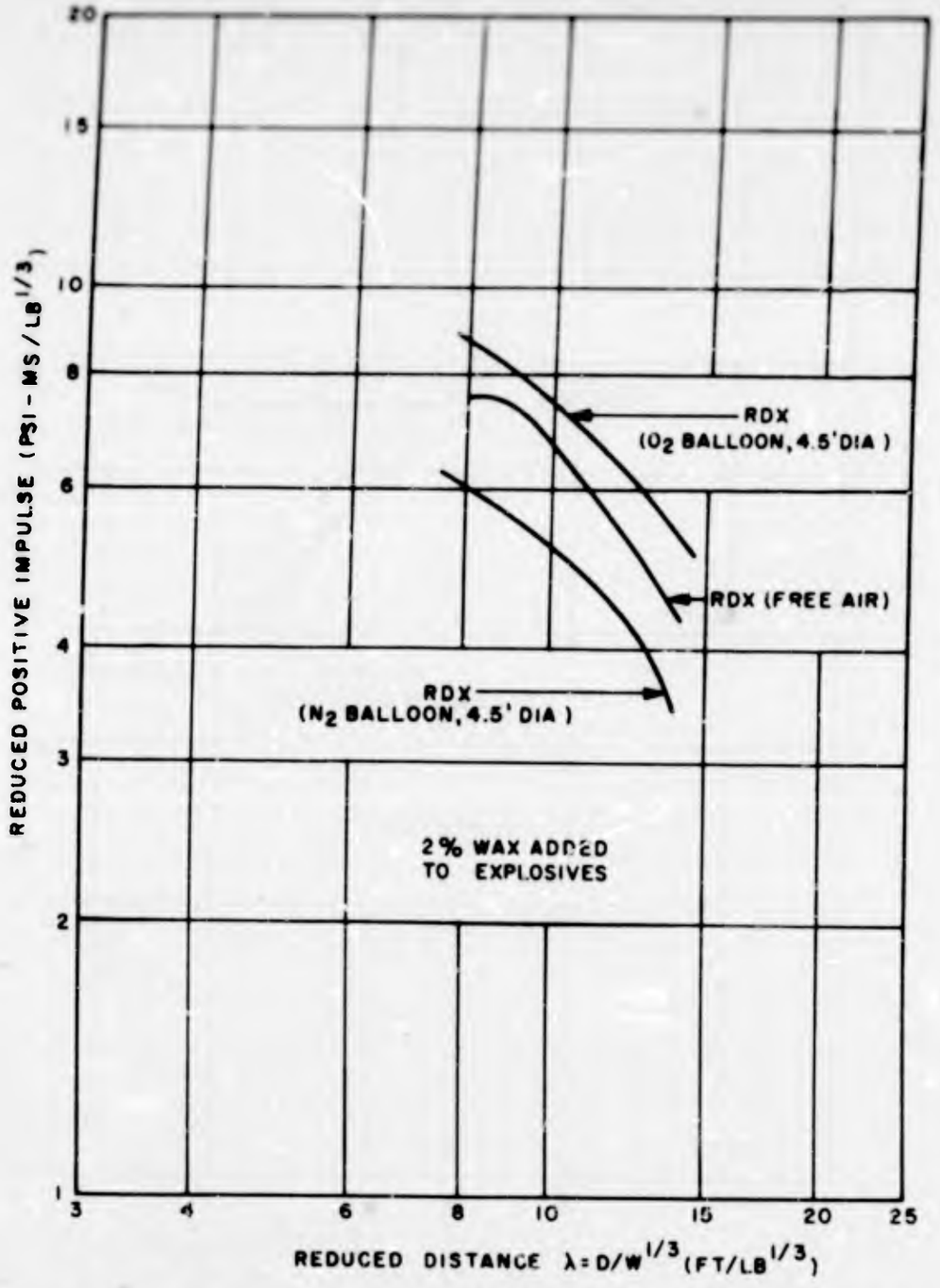


FIG. 10 REDUCED POSITIVE IMPULSE VS REDUCED DISTANCE AS A FUNCTION OF OXYGEN CONCENTRATION IN TEST GAS: RDX RESULTS

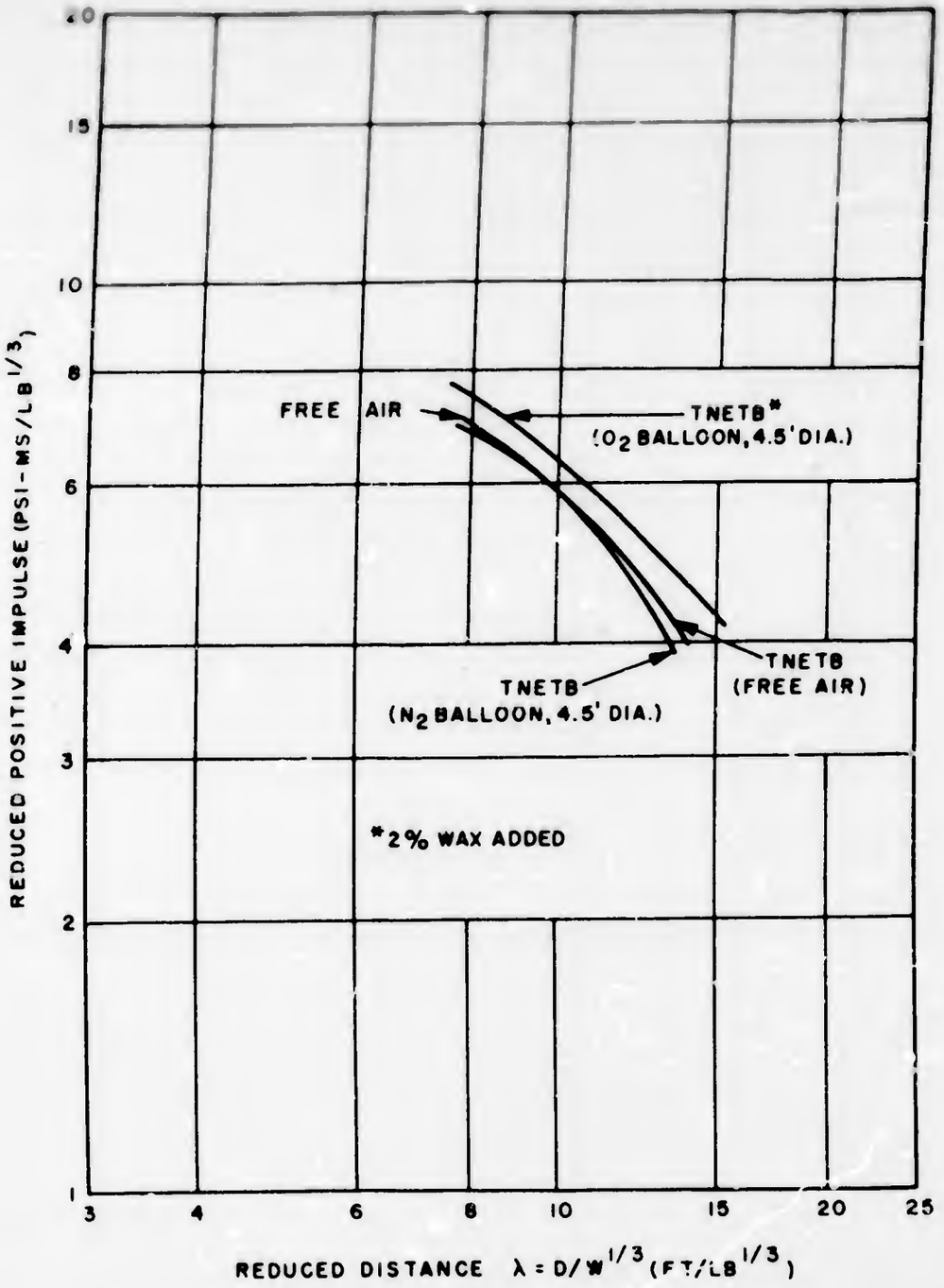


FIG. 11 REDUCED POSITIVE IMPULSE VS REDUCED DISTANCE AS A FUNCTION OF OXYGEN CONCENTRATION IN TEST GAS: TNETB RESULTS

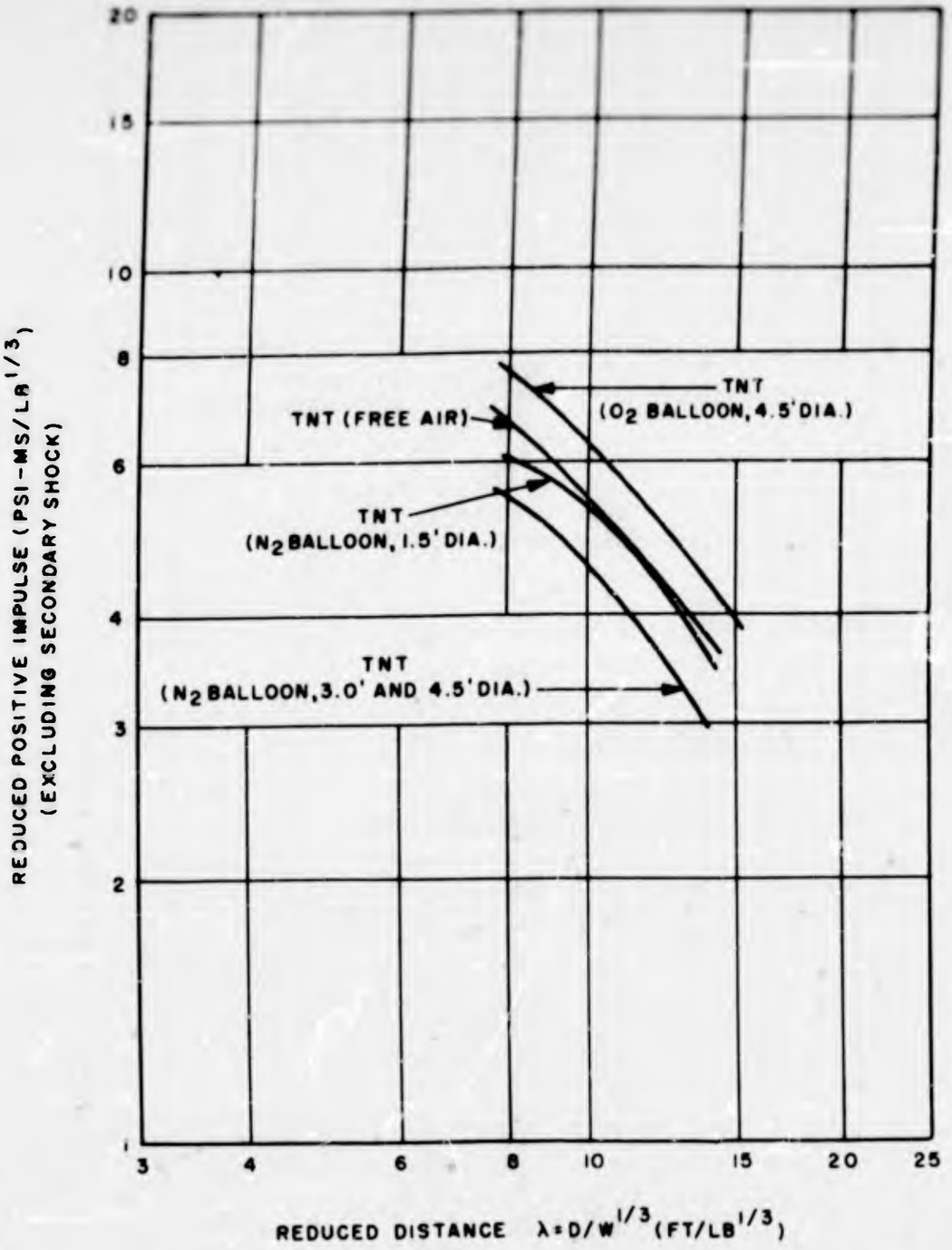


FIG. 12 REDUCED POSITIVE IMPULSE (EXCLUDING SECONDARY SHOCK) AS A FUNCTION OF BOTH OXYGEN CONCENTRATION IN TEST GAS AND BALLOON SIZE: TNT RESULTS

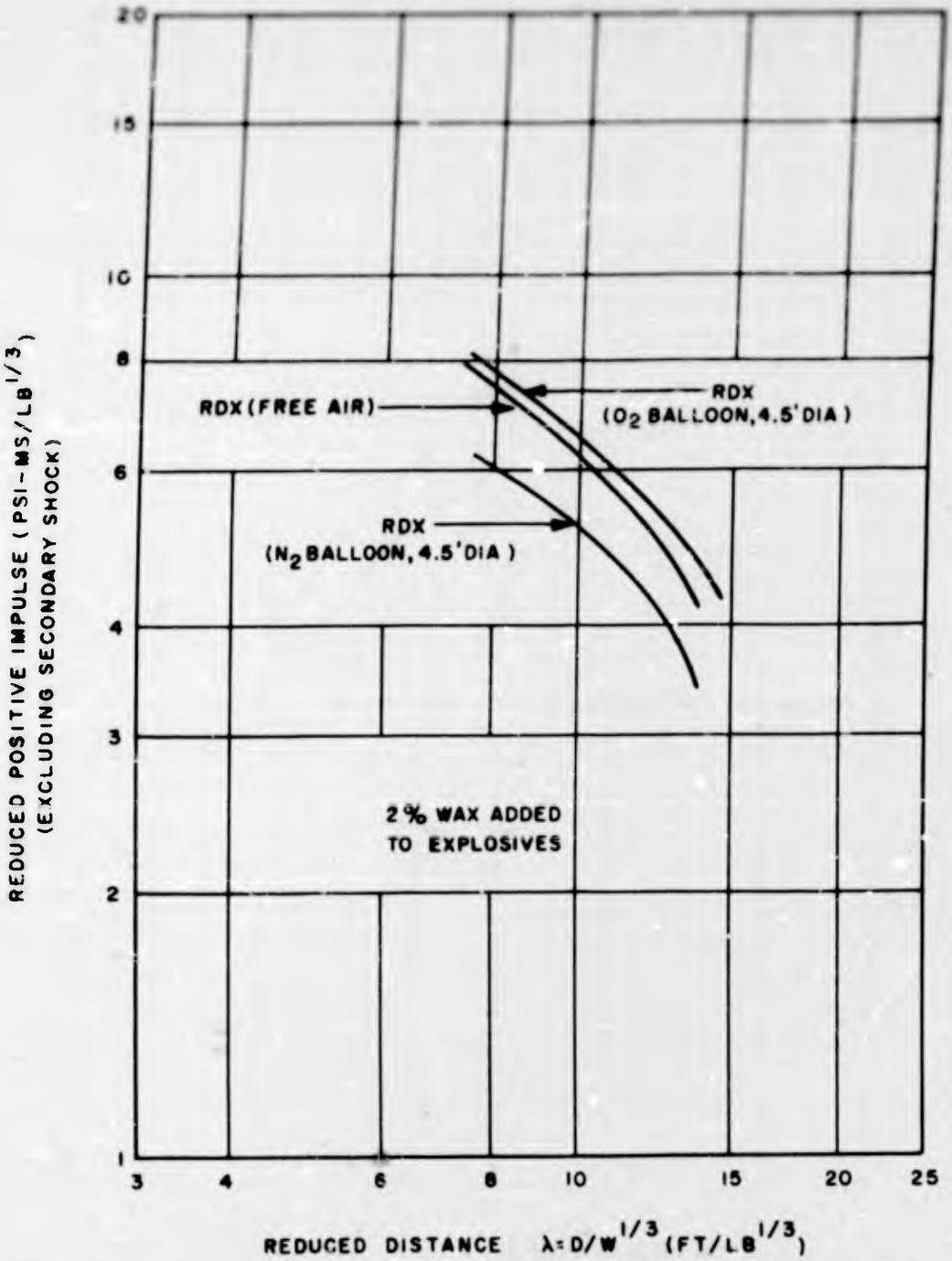


FIG. 13 REDUCED POSITIVE IMPULSE (EXCLUDING SECONDARY SHOCK) VS REDUCED DISTANCE AS A FUNCTION OF OXYGEN CONCENTRATION IN TEST GAS: RDX RESULTS

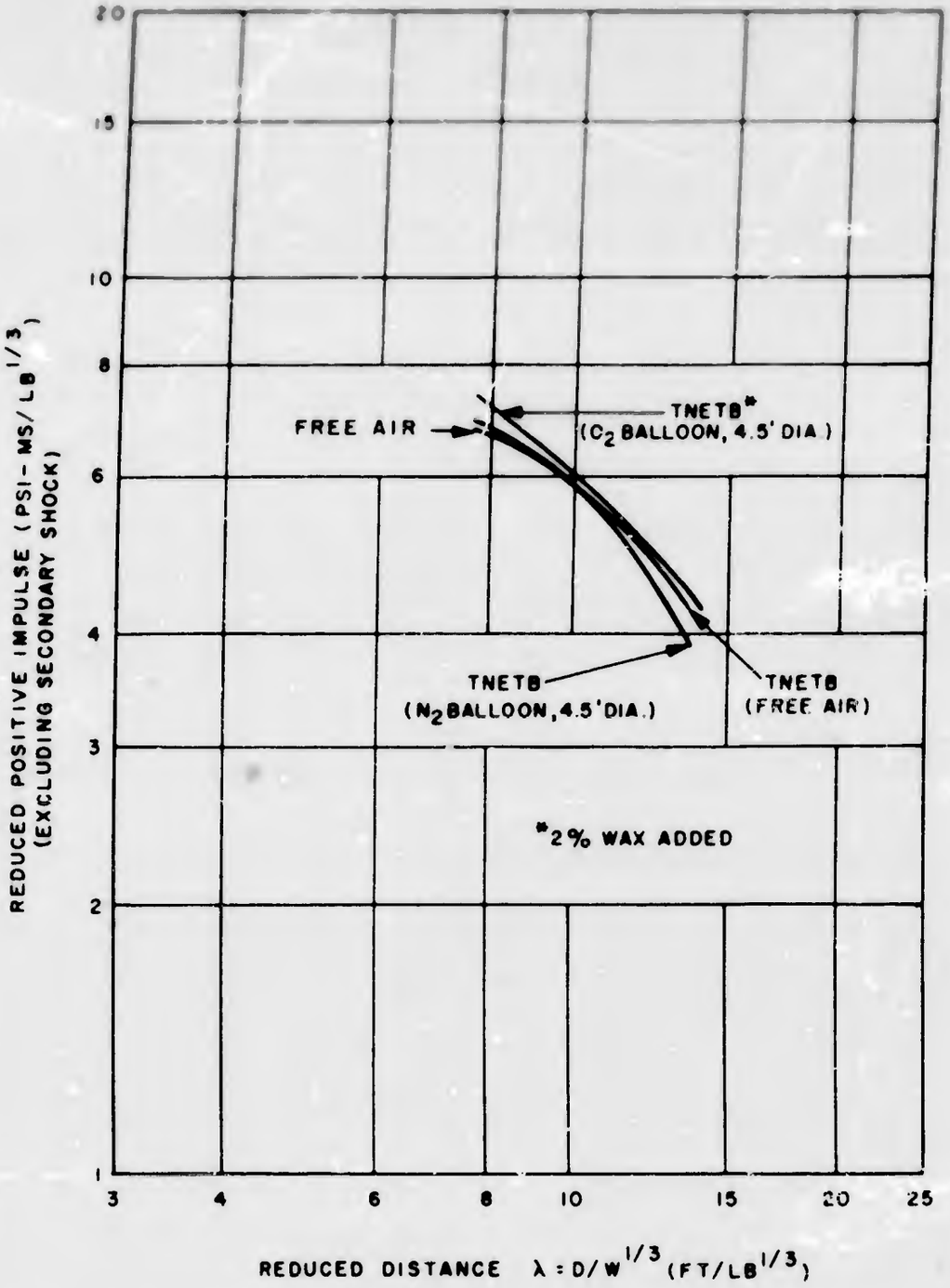
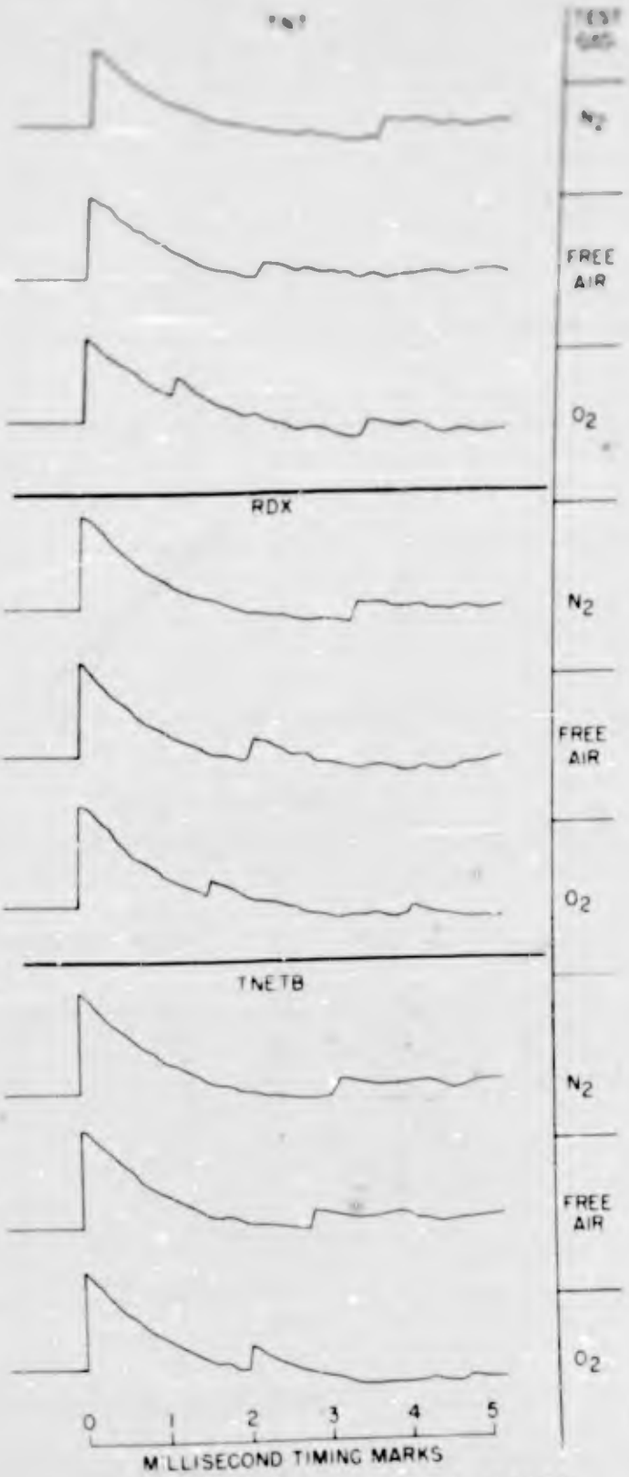


FIG. 14 REDUCED POSITIVE IMPULSE (EXCLUDING SECONDARY SHOCK) VS REDUCED DISTANCE AS A FUNCTION OF OXYGEN CONCENTRATION IN TEST GAS: TNETB RESULTS



NOTE CHARGE TO GAGE DISTANCE = 770 FT FOR ALL RECORDS

FIG. 15 PRESSURE-TIME RECORDS SHOWING THE EFFECT OF AFTERBURNING ON POSITION OF SECONDARY SHOCK

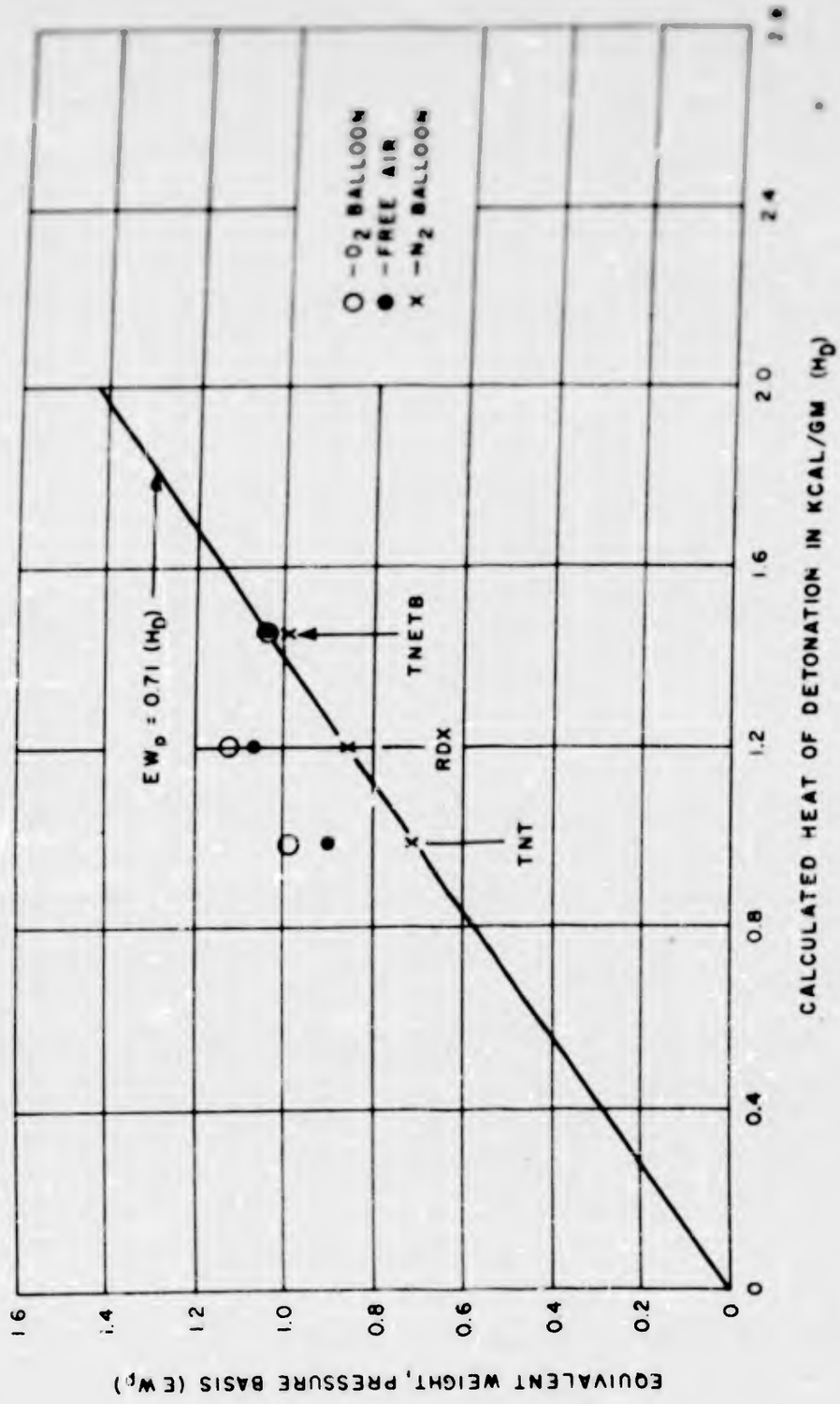


FIG. 16 EQUIVALENT WEIGHT (PRESSURE BASIS)
VS HEAT OF DETONATION (H_2O, CO, CO_2 MECHANISM)

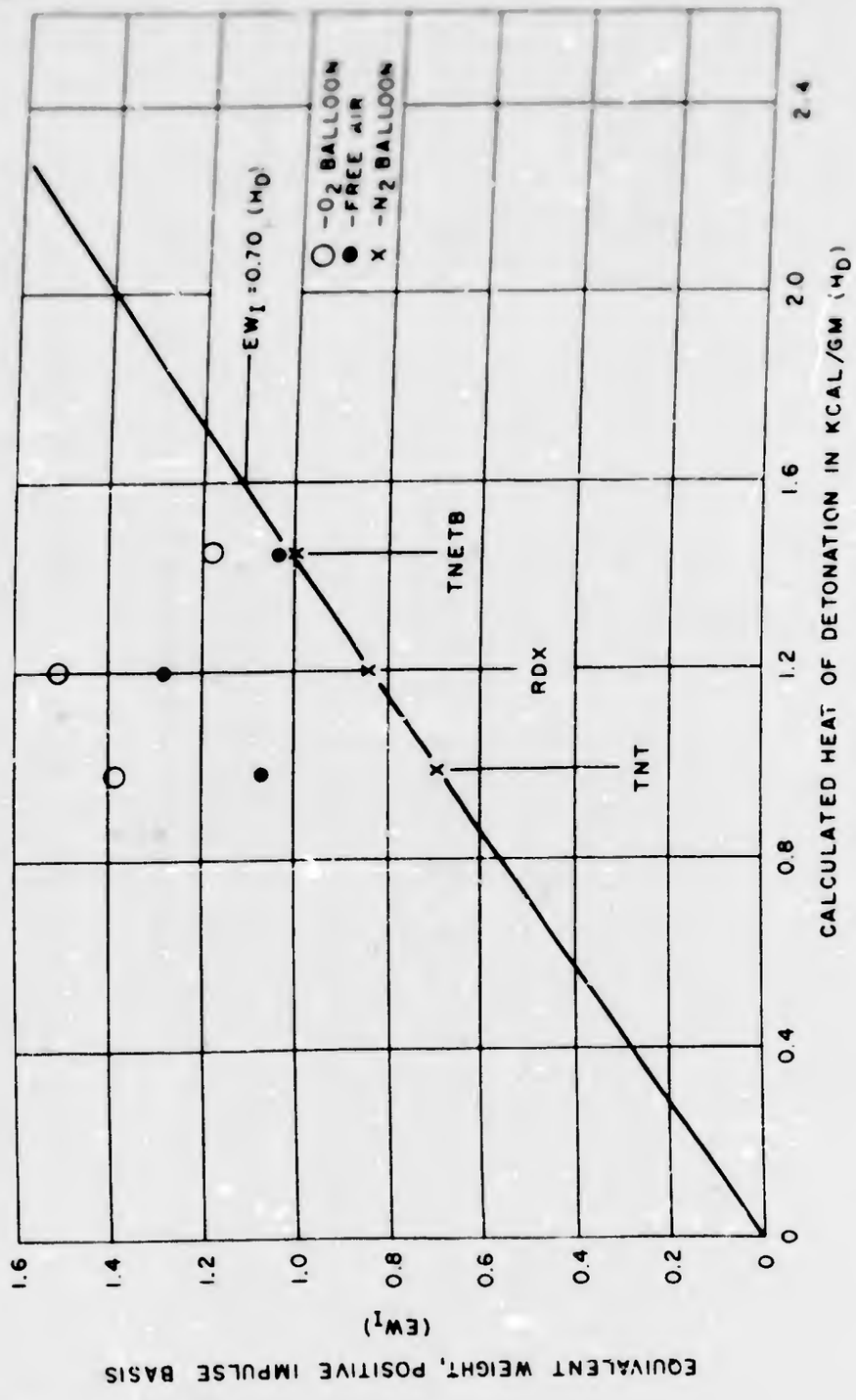


FIG. 17 EQUIVALENT WEIGHT (POSITIVE IMPULSE BASIS) VS HEAT OF DETONATION (H_2O, CO, CO_2 MECHANISM)

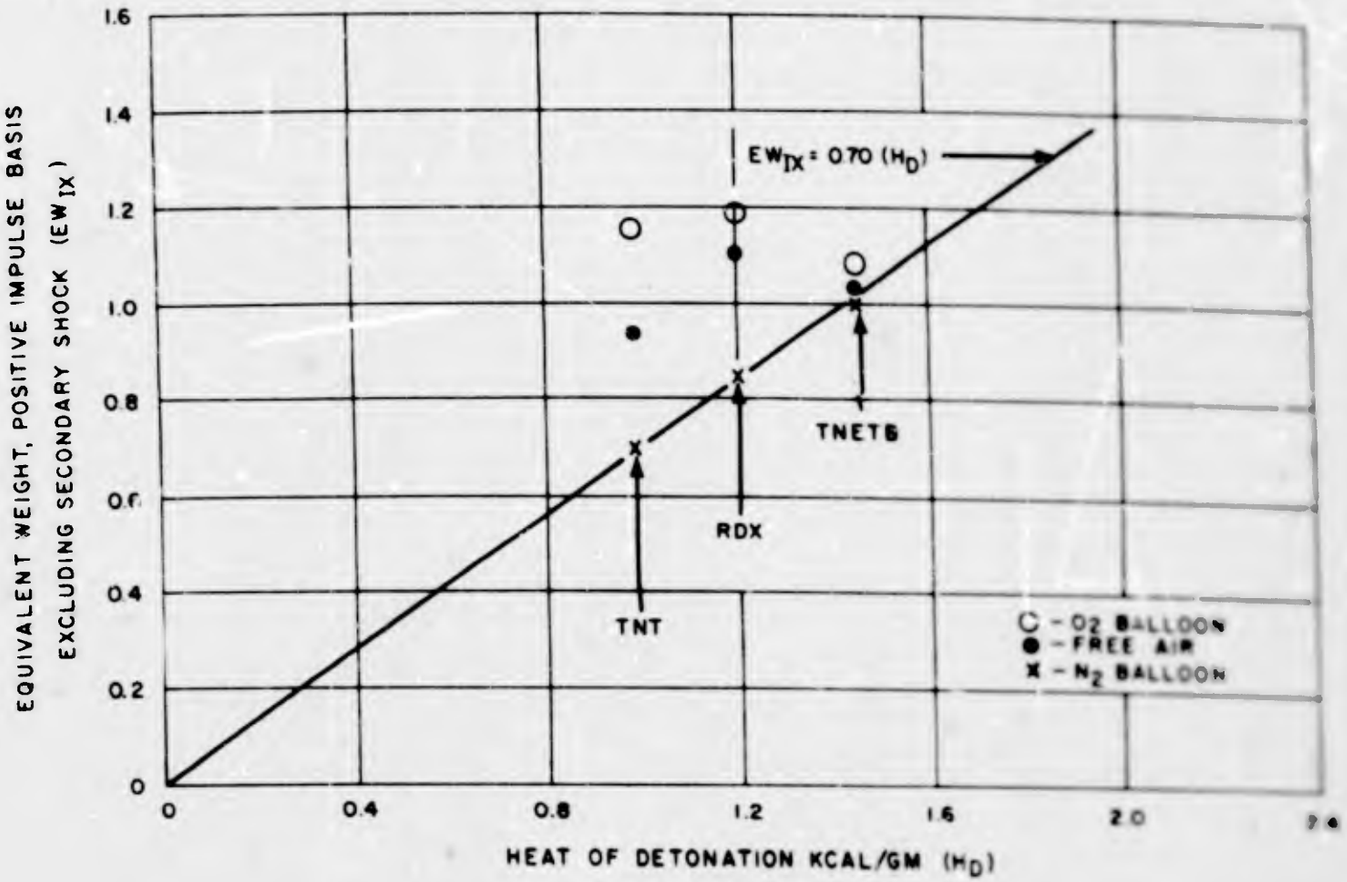


FIG. 18 EQUIVALENT WEIGHT (POSITIVE IMPULSE BASIS, EXCLUDING SECONDARY SHOCK) VS HEAT OF DETONATION (H_2O, CO, CO_2 MECHANISM)

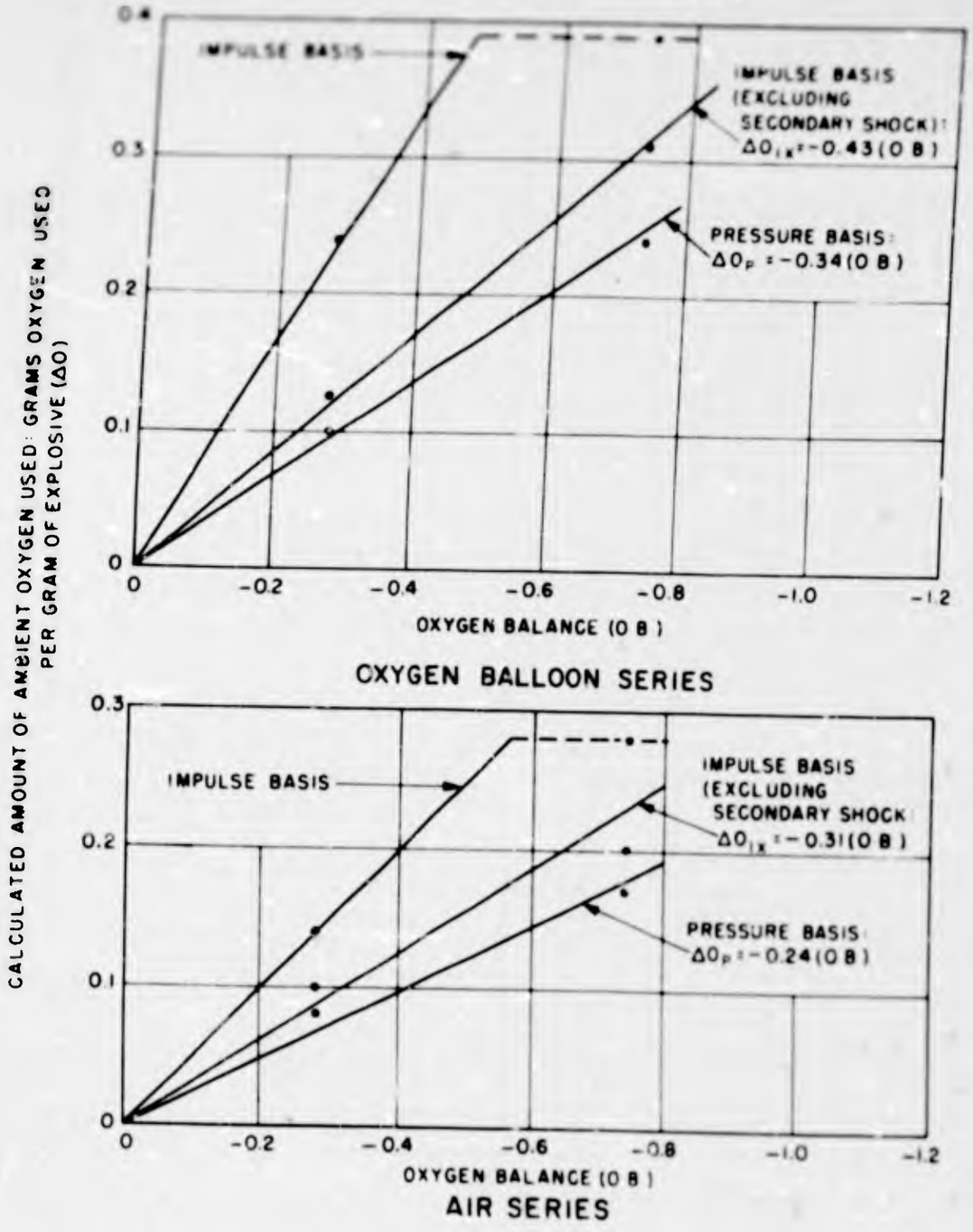


FIG. 19 CALCULATED AMOUNTS OF AMBIENT OXYGEN UTILIZED IN THE AFTERBURNING PROCESS, AS A FUNCTION OF EXPLOSIVE OXYGEN BALANCE (INCLUDING LEAST SQUARE FITTED LINES)

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