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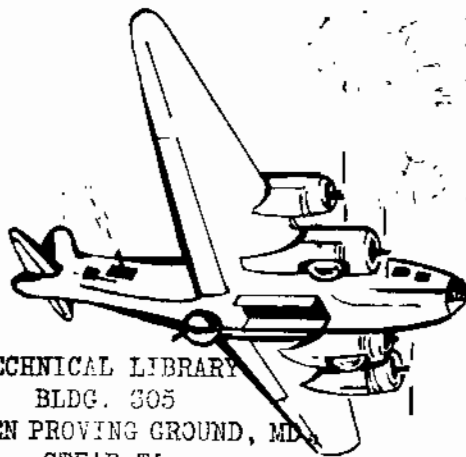
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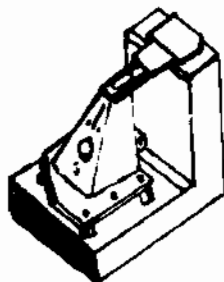


Effectiveness of Incendiary Ammunition
Against Aircraft Fuel Tanks

Arthur Stein

Mary Gene Torsch

TECHNICAL INFORMATION BRANCH
ORDNANCE RESEARCH CENTER
ABERDEEN PROVING GROUND
MARYLAND



M-484

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Against Aircraft Fuel Tanks**

**MEMORANDUM
REPORT No. 484**

**PROJECT NO. TB3-0238A OF THE RESEARCH AND
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BALLISTIC RESEARCH LABORATORIES
MEMORANDUM REPORT NO. 484

Stein/Torch/mne
Aberdeen Proving Ground, Md.
11 August 1948

EFFECTIVENESS OF INCENDIARY AMMUNITION AGAINST AIRCRAFT FUEL TANKS

ABSTRACT

The probability of obtaining a kill on an aircraft due to the vulnerability of its fuel system to incendiary projectiles is the product of the probability that a round perforates the tank, the probability that the projectile functions, the probability that the penetrating projectile ignites the fuel after functioning and perforating, the probability that the tank does not self-seal and the probability that a resulting fire causes a kill to the aircraft. These various probabilities have been obtained as functions of striking velocity from firings of incendiary ammunition against gasoline and kerosene filled fuel tanks. Experiments under controlled conditions, designed to study the mechanics of fuel tank ignition, are described and preliminary results presented. A formula is given which utilizes the tabulated data to give the total probability of fuel tank fire in "n" hits on the plane as a function of both the single-shot probability of fire and the probability of fire due to impacting an already leaking fuel cell.

INTRODUCTION

One of the most economical methods of obtaining killing damage to an aircraft is by liberating destructively the energy contained within the fuel it carries.

This report presents results obtained to date in all firings against aircraft fuel systems conducted at Aberdeen Proving Ground in the current vulnerability firings, with the exception of fragment damage. Additional firings are now in progress and much analysis remains to be done. Current tests include firings of bare TNT and also of shaped charges against aircraft fuel cells. The current program also proposes to analyse the mechanism of fuel tank ignition through study of the fuel tank spray, duration and type of projectile functioning, the effect of altitude and speed of aircraft and the effect of changes in type of fuel and in fuel tank and line construction. Partial results of the current program are presented in this report. The study of fuel tank damage by fragments is in progress and will be separately treated.

The factors affecting fuel tank ignition are quite varied and many have been studied at other agencies. Those studies most pertinent to the present report have been cited.

Probably the best available reference on the history, design, development and characteristics of incendiary ammunition is the volume issued by the Office, Chief of Ordnance.¹ In addition to detailed description of all of the incendiary ammunition developed by the Ordnance Department, and discussion of test results, this report contains an exhaustive list of references, particularly to hundreds of Ordnance Committee Meeting items and firing records which could not otherwise be located in a reasonable length of time.

FUEL TANK IGNITION BY INCENDIARY AMMUNITION

The purpose of the firings against the aircraft target is to evaluate the vulnerability, not of these particular aircraft, but of aircraft of the future. Hence, the data to be obtained must be in a form which will permit evaluation of the vulnerability of many types of fuel tank installations. The following remarks indicate a manner in which this may be done.

The net single-shot probability of obtaining an "A" kill² due to ignition of a particular fuel tank or cell, for a random hit on the plane, is

$$P_{A_F} = (P_{H/plane}) (P_{CP/H}) (P_{fcn/CP}) (P_{F/fcn, CP}) (P_{A/F}),$$

¹Record of Army Ordnance Research and Development, Volume 2, Small Arms and Small Arms Ammunition, Book 2 Small Arms Ammunition (C).

²An "A" kill is one which causes the aircraft to fall within five minutes. Complete definition of the different categories under which damage is assessed at Aberdeen are to be found in BRL 462 "Aircraft Vulnerability and Overall Armament Effectiveness."

where¹

(P H/plane = probability of hitting the projected area of the tank if the plane is hit,

(P CP/H = probability of a cell wall perforation if the projected area of the cell is hit,

(P fcn/CP) = probability that a round functions, i.e., itself ignites,

(P F/fcn, CP) = probability of igniting a fuel cell if the round functions (and perforates) the cell,

(P A/F) = probability of an "A" kill on the plane if the fuel is ignited.

The corresponding expression for so-called "compound" damage, the probability of obtaining an "A" kill by an impact into a previously damaged and leaking tank, is developed in a previous report,² and presented in Appendix B.

The several factors in the foregoing expression for the net probability of obtaining an "A" kill, vary differently with change in striking velocity. It is evident that the probability of an "A" kill on any aircraft due to fuel tank fire is not obtainable solely from field firings against aircraft.

The factor (P H/plane) is equal to the relative projected area of the fuel tank, which area is obtained in the current effectiveness studies at Aberdeen by planimentering photographs of skeletal models.

Figure 1 is such a photograph of the XB-47 jet bomber.

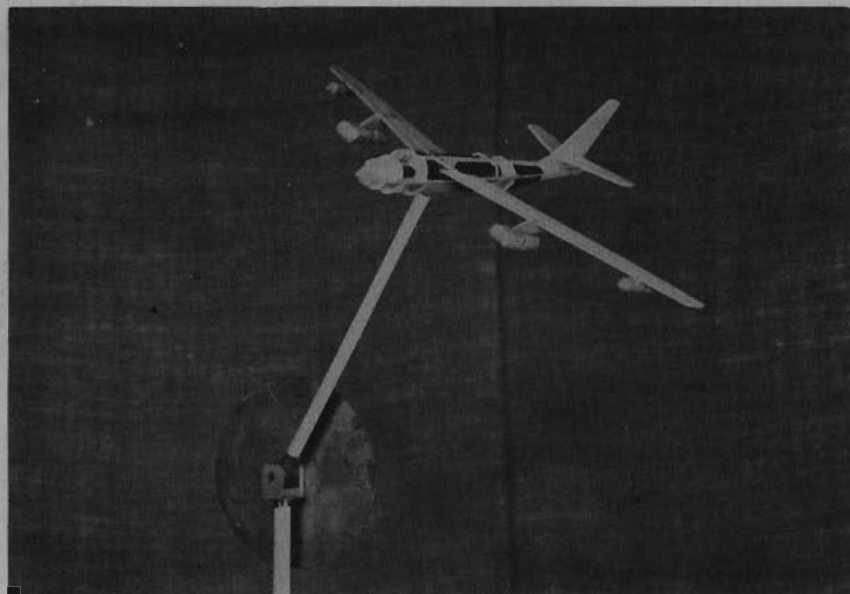


FIG. 1 Optimum Caliber Program. View of XB-47 Model simulating range of 185 yards.

¹Thus, if (P H/plane) = .05, (P CP/H) = .90, (P fcn/CP) = .80, P F/fcn, CP) = .20 and (P A/F) = .50, then the net single-shot probability, $P_{A/F} = .0036$. The probability of an "A" kill due to fire in the target tank for 20 random hits on the plane is then $= 1 - e^{-20(.0036)} = .07$.

²BRL Memorandum Report No. 437. "Optimum Caliber Program," 1 July 1946.

The probability ($P_{CP/H}$), of a cell perforation if the projected area of the tank is hit, is obtained both from field firings and also, when fuel cells are masked by heavy dural or armor plate, by means of theoretical penetration laws. The field firings have been conducted against a large variety of fuel tank installations and consequently an installation will have been used as a target which is not significantly different from the installation on a plane under study. The sample number for the field firings is larger for the determination of ($P_{CP/H}$) than for $P_{F/fcn, CP}$ or ($P_{A/F}$) since the same data for ($P_{CP/H}$) apply equally for gasoline or kerosene filled cells and for single-shot and compound hits.

The factor ($P_{fcn/CP}$), the probability that a round which penetrates the cell has functioned, also does not depend on the type of fuel or on whether there was previous leakage in the area. Consequently, here too it has been possible to obtain a relatively large sample size from the field firings.

It should be emphasized that the probability of functioning does not of itself adequately describe the contribution to fuel tank ignition of the functioning characteristics of the ammunition. This is true even when data is available describing the variation in the probability of functioning with variations of striking velocity, spin, obliquity, target thickness and composition. Two types of projectiles may have the same probability of functioning but may differ markedly in how the functioning occurs. Important differences may be found in the distance from the target plate (or wing skin) to the initial point of functioning and in the length, intensity and duration of flash produced. There is in progress a series of firings, proposed by Mr. F. E. Watts of A & A Division, Development and Proof Services, Aberdeen Proving Ground, of various types of incendiary ammunition to determine its functioning against dural plate of various thicknesses. These firings are being conducted over a wide range of striking velocities and for impacts on the plate at several obliquities. A short summary of preliminary results appears in a later section herein on results of supplementary tests.

The probability ($P_{F/fcn, CP}$), that a projectile which functions and perforates a fuel cell wall will ignite the contents, depends markedly on the type of fuel and on whether there was any previous leakage in the area. A study of the mechanism of ignition involves consideration of the striking velocity and mass of the projectile, the position, degree and duration of the incendiary functioning, the manner in which the nose of the projectile is blunted when it strikes the aircraft skin, the delay before spray emerges from the tank after impact, the degree of this spray, the size, shape and self-sealing properties of the tank, the amount and type of fuel it contains, the location of the impact on the tank and the environmental conditions such as altitude, temperature, confinement of space about tank, location of tank in wing, protection of hole in tank from the effects of the slip-stream, structural material which is inflammable, and the like.

The effects of variations in the factors affecting fuel cell ignition are currently being studied under more controlled conditions than are possible by the firing against aircraft targets. The progress made to date in these studies is indicated in a later section on supplementary tests.

The last factor, ($P_{A/F}$), is the probability that the ignited tank will cause an "A" kill on the plane (and similarly for "B", "C" and "E" damage). This factor depends on the amount of fuel feeding the fire and on the location and function of the tank in the fuel system. For the aircraft used as targets in the field firings, fires are assessed by experts from the Navy and Air Force as to whether or not the damage is "A" damage. The assessments of damage to aircraft on the ground are intended to be estimates of the impairment of performance that would have occurred had the aircraft been in flight. For new aircraft, not fired upon, the

probability of a kill when a fire occurs is estimated by the Air Force assessors. This estimate depends on the location of the tank in the plane and the probable severity of fire for the type of ammunition or fragment under study. The probable severity of fire in turn is estimated from the field trials which determine the average amount of leakage obtained by the test ammunition.

RESULTS OF FIRINGS AGAINST FUEL CELLS IN AIRCRAFT WINGS

Incendiary Bullet Impacts. The results of field trials against the P-38 conducted up to 1 January 1948 are presented for various types of incendiary bullets in Table I. The listing of the firing records describing damage in detail appears in Appendix D. Partial results are included for the current series of 2000 yard firings of Cal. 0.60 and 20mm ammunition. It is expected that the final results will be incorporated in Table I and presented in a future report, as will the final results of the current series of **functioning tests** against various thicknesses of Alclad at a number of obliquities and over a wide range of striking velocities.

The various conditional probabilities appearing in the formula for $P_{A/F}$, are defined as ratios in Table I to indicate their origin. Thus $(P F/fcn, CP)$ is the ratio $\frac{F_{ss}}{CP_{ss}}$ for single-shot fire, and $\frac{F_c}{CP_c}$ for compound fires. Similarly,

$$(P A/F) = \bar{A}_{F_{ss}} \text{ or } \bar{A}_{F_c}$$

for single shot or compound fires, respectively and

$$(P CP/H) = \frac{CP_{ss}}{H_{ss}} \text{ or } \frac{CP_c}{H_c} .$$

$(P fcn/CP)$ may also be computed from Table I as the ratio of "hits excluding duds" to "hits including duds". In Table I, the line of fire is designated by both the angle θ , which is the angle in a horizontal plane between the line of fire and the longitudinal axis of the fuselage and the angle ϕ , which is the angle that the plane of the wings makes with the horizontal. The plane of the wings is defined as the plane passing through the leading and trailing edges. "Leading edge up" is referred to as a positive angle for ϕ and "leading edge down" as negative. It is not necessary to distinguish between positive and negative values of θ because of the symmetry in the horizontal plane about the longitudinal axis for the cases considered.

The results of firings against other aircraft types have been tabulated in BRLM 462. Graphs of these results appear in the present report as well. The description of the fuel tank installations for the various aircraft targets also appear in BRLM 462.

No attempt at thorough explanation of observed differences will be made at this time. It is hoped to present a complete statistical analysis at the conclusion of the firings. The observed results are plotted in Figures 2 through 25. Since some firings are still in progress, confidence intervals have not been shown on the figures. However, the sample sizes are indicated at each observational point and so such intervals may be readily computed if desired.

The P-38 was fired upon from two directions, (1) from the front, the line of fire making an azimuthal angle $\theta = 20^\circ$ in the horizontal plane with the longitudinal axis of the plane and a vertical angle $\phi = 13^\circ$ with

the plane of the wings, impacting the lower skin, and (2) from the rear, with $\theta = 20^\circ$ again and $\phi = -13^\circ$; that is making an angle of 13° with the plane of the wings and impacting the upper skin. These two directions were also employed in the firings against fuel cells installed in other types of aircraft. Hereinafter these two directions are designated simply "front below" and "rear above".

Figure 2 presents the fraction of those rounds impacting on P-38 wings, which functioned as a result of impact. Functioning was recorded by proof directors and assessors both from observation of visual flash and by examination of impact area for characteristic blackening and charring effects.

For functioning, one may combine impacts, with no regard as to whether tanks were filled with gasoline or kerosene and whether or not there was previous leakage in the wing. Since no significant differences were obtained in functioning for firing from the front as compared to firing from the rear, the results for the two directions were combined in Figure 2. Upon the completion of the current functioning tests described in a later section it will be possible to study the relation between functioning on simple sheets of alclad and functioning on the more complex wing structure. It is possible to alter the sensitivity of small arms incendiary bullets (which function by nose friction effect) and thus effectively increase the probability of proper functioning at the lower striking velocities. The sensitivity may be adjusted to give functioning at a closer location on a specific target. The Heinkel type target has been used for this purpose in the past.¹ A major problem is the definition and description of the target to be encountered.

The same problem exists in part for fusing of high explosive shell. The M75 fuze assembled in the 20mm, HEI, M97 has shown erratic functioning in most phases of the firings against aircraft targets. This is a relatively insensitive fuze whose functioning depends markedly on the thickness of the target material. The requirements for consistent and proper functioning of a fuze for this size and type of high explosive shell will be demonstrated in a following section of this report.

Figure 3 depicts the observed probability of functioning for impacts on all target planes combined.

Figures 4 and 5 show the observed probabilities that projectiles which impact on the projected area of a P-38 fuel tank will perforate the tank wall. A projectile may impact the projected area and not perforate a tank due to ricochet or insufficient remaining velocity.

Figures 6 and 7 present the combined results for firings against the P-38, P-59, A-35 and B-25. The latter three aircraft were employed as fuel tank targets at the one range of 500 yards. Cell perforation does not depend on the type of fuel or on the presence of leakage from previous hits. Consequently the gasoline and kerosene filled tanks and the single shot and compound hits were combined for Figures 4 through 7.

Figures 8 and 9 show the observed single-shot probability of obtaining fires for gasoline and for kerosene filled tanks. For these figures, all functioning perforations were considered for projectiles impacting on previously undamaged cells and in areas in which there was no fuel leakage due to any reason. The data for front below and rear above were combined. Figures 10 and 11 present the observed compound probabilities for obtaining fires when perforations are obtained through previously damaged and leaking cells (or cells in a region in which fuel has been observed outside the tanks for any reason).

Figures 12 through 15 are a similar series which include non-functioning hits in the number of

¹Record of Army Ordnance Research and Development, Volume 2, Small Arms and Small Arms Ammunition, Book 2, Small Arms Ammunition (C).

perforations. Figures 18 through 19 also include non-functioning hits in the number of cell perforations, but the data from firings at a range of 500 yards have now been augmented by inclusion of firings against the P-59, A-35 and B-25.

It is interesting at this time to present a previously unpublished chart, Figure 19a, prepared by Colonel R. R. Studler, Ordnance Department, depicting the probability of obtaining ignition on a Heinkel replica target. A description of the Heinkel targets and the firings against them is given in the Ordnance Department manual on Small Arms Ammunition.¹ A typical Heinkel replica arrangement is shown in Figure 19b.

The difference which will be noted between the values given in this chart and the results reported in the present study may be attributed to the difference between the Heinkel replica target and the P-38 structure and also to the difference in conditions of the experiment. For example, a slipstream was directed over the P-38 target but not over the Heinkel.

Figures 20 through 23 illustrate the average single-shot "A" and "E" assessments given by the Air Force assessors to the observed fires. These charts are highly erratic in the sense that the graphs are not monotonically increasing with increasing striking velocity. The sample sizes for these figures are the smallest of all since not very many hits resulted in fires. These figures are not the result of observed fact only, such as those described previously, but include assessor opinion. It should be remembered that the stream of air provided over the target wings by the slave engine is extremely effective in extinguishing fires with external sources. The air stream over the target wings usually was from 80 to 100 mph and often after the slave engine was shut off a large fire would immediately flare where previously only smoke was seen. Tests conducted by Wright Field indicate that if a fire is not blown out by the time a plane is traveling at about 110 mph then it would not be blown out at any speed and probably has an internal source, protected from the air stream.²

Although assessments are made as though the aircraft were in actual flight there is obviously much room for difference of opinion. An attempt has been made to determine the average difference of assessments of the same damage by having more than one assessor give an independent assessment. These results have not yet been analyzed. It is noted, however, that **much damage** is either obviously non-lethal or obviously lethal. Such damage receives OA or 100A assessments and constitutes over 90% of the observed data. The "B" damage assessments are more reliable than the "A" assessments since it is much easier to determine whether the damage is lethal within 2 hours than within 5 minutes. In this regard it is interesting to note that many reports of battle damage sustained in the last war indicate that few aircraft that caught fire returned to base. The (P A/F) factor in the calculation of the probability of "A" damage due to fuel sustained by any target aircraft under study will usually have a different value than is indicated in the Figures 20 - 23 since the seriousness of fire will depend on the location of the tank and on the availability and efficiency of fire extinguishing equipment.

¹Record of Army Ordnance Research and Development, Volume 2, Small Arms and Small Arms Ammunition, Book 2, Small Arms Ammunition (C).

²TSEPP-144-1698, "Summary of Data on Fires and Explosions in Aircraft Fuel Tanks," 13 Sept. 1946, Appendix I, page 9.

The observed probabilities of obtaining self-sealing as a function of striking velocity are indicated in Figures 24 and 25 for gasoline and kerosene. It should be noted that both the fracture of the nose and the tumbling of incendiary projectiles influence the self-sealing property of tanks. Most American self-sealing tanks have been designed to prevent "defeat" by Cal. 0.50 AP ammunition. That is to say, they are intended to effectively seal a specified number of penetrations by this caliber. So long as the penetration of the tank occurs by puncture, as from normal impact by a streamlined bullet, these tanks may seal Cal. 0.60 and often even 20mm projectiles. However, so-called "plugging" of the tank, where a piece of the tank is actually removed, will usually result in its defeat. An incendiary bullet may assist this "plugging" action by burning of rubber and by virtue of the break-up of the nose, resulting in a penetration by a jagged blunt nose. Thus, too, jagged irregular fragments of the same weight as the Cal. 0.50 bullet (about 700 grains) will also result in plugging and consequent defeat of the self-sealing action. The method whereby the nose of an incendiary bullet breaks is strikingly exhibited by a series of radiographic studies conducted at Frankford Arsenal.^{1, 2}

In this report results have been expressed in terms of striking velocity rather than ground range. Figure 25a shows the relationship between striking velocity and ground range when the bullets are fired from a stationary gun.

Empirical Formulae. The usefulness of the experimental data presented in this report depends, in part, upon the extent to which it can be extrapolated to designs of ammunition which have not been fired. Empirical formulae fitting the experimental data are an aid to such extrapolation.

An empirical formula has been proposed by Mr. H. K. Weiss to fit the information presented in Figure 8, the fires per cell penetration, on P-38 gasoline-filled fuel cells. It is

$$p_f = 1 - 2.3 \exp -1.1 v_s w_p^{1/2} w_f^{1/4}$$

where

$$p_f = \text{fires per cell penetration} = F_{ss}/CP_{ss}$$

$$v_s = \text{striking velocity in units of 1000 ft/sec}$$

$$w_p = \text{projectile weight in units of 1000 grains}$$

$$w_f = \text{filler weight in units of 100 grains}$$

As a typical example of the use of the formula, consider the T36E2 Cal. 0.60 round striking at 2100 ft./sec. The projectile weight is 1150 grains and the filler weight is 92 grains. The formula yields a value of p_f

$$\begin{aligned} p_f &= 1 - 2.3 \exp (-1.1) (2.1) (1.15)^{1/2} (.92)^{1/4} \\ &= 0.80 \end{aligned}$$

The value from Figure 8 is 0.78, which however, is a closer match than is obtained for some of the other points. Figure 26b shows p_f computed from the formula for the five incendiary and armor piercing rounds of Figure 8. Also shown in Figure 26b are the experimental points given in Figure 8.

¹FA T2161, "X-Ray Pictures of Current Production Caliber .30 M1 Incendiary Bullets During Performance Tests", E. R. Thilo.

²FA R-321 "X-Ray Pictures of Current Production Caliber 0.50 M1 Incendiary During Performance Tests, First Report", E. R. Thilo, May 1943.

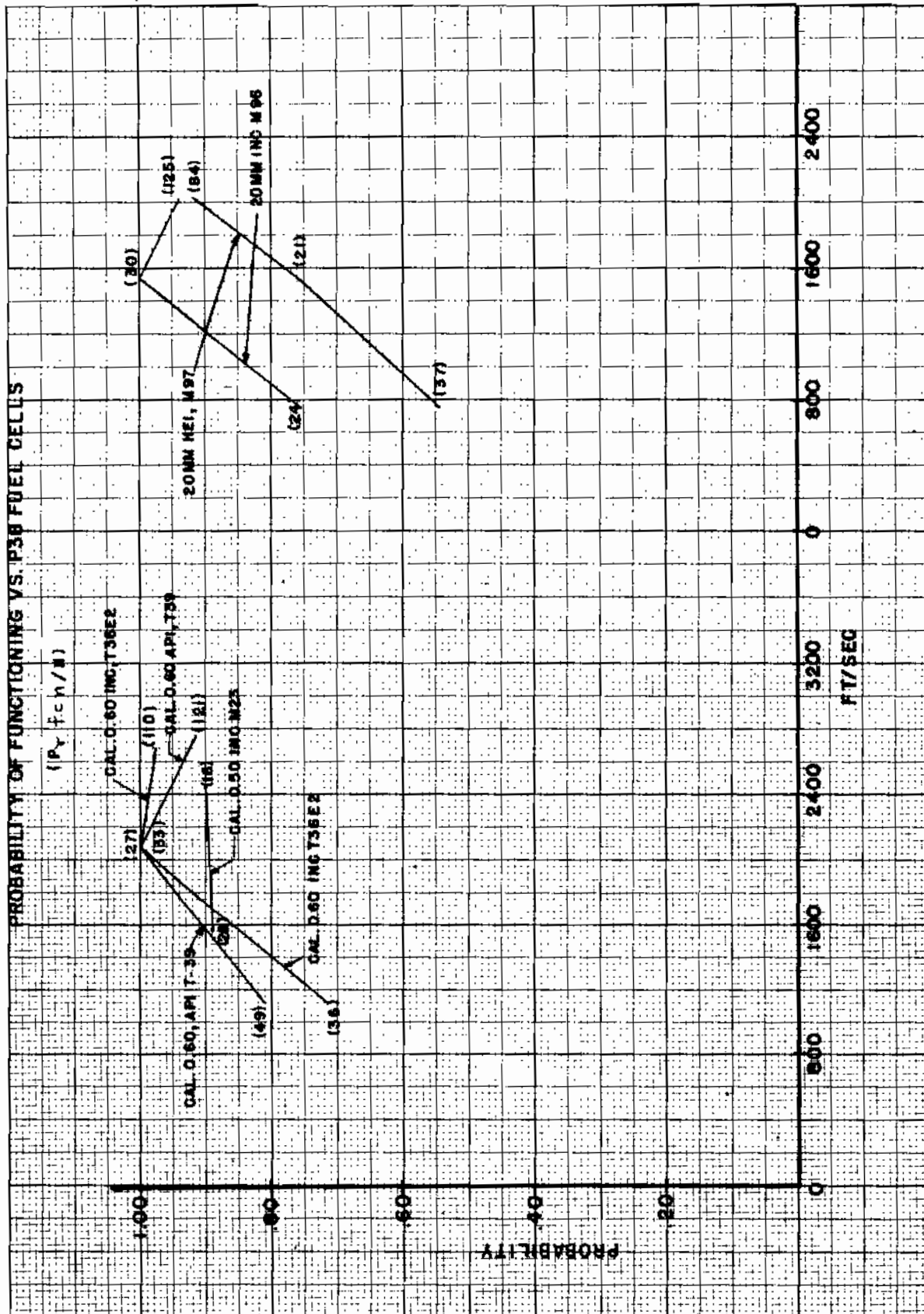


FIG. 2

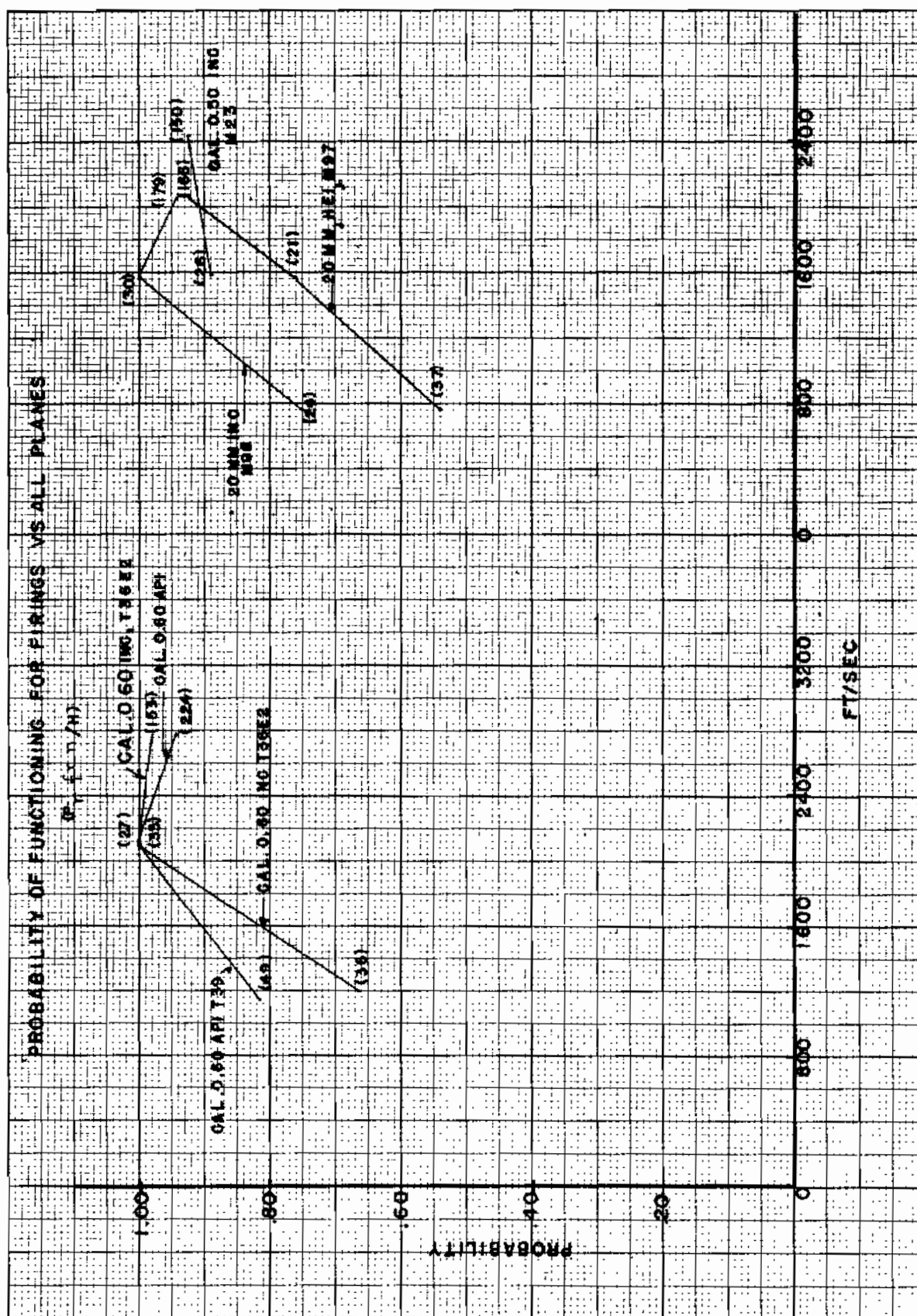


FIG. 3

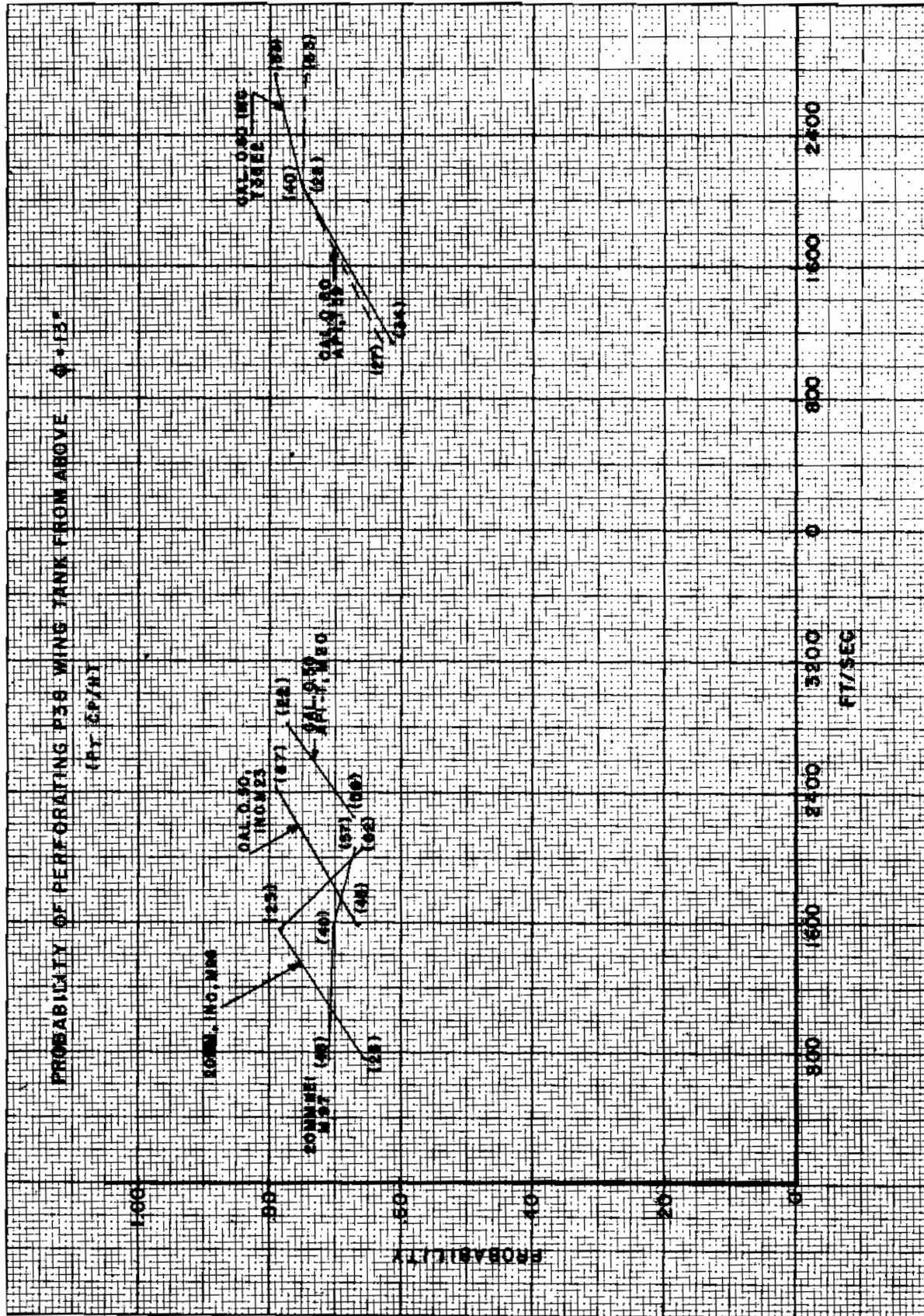
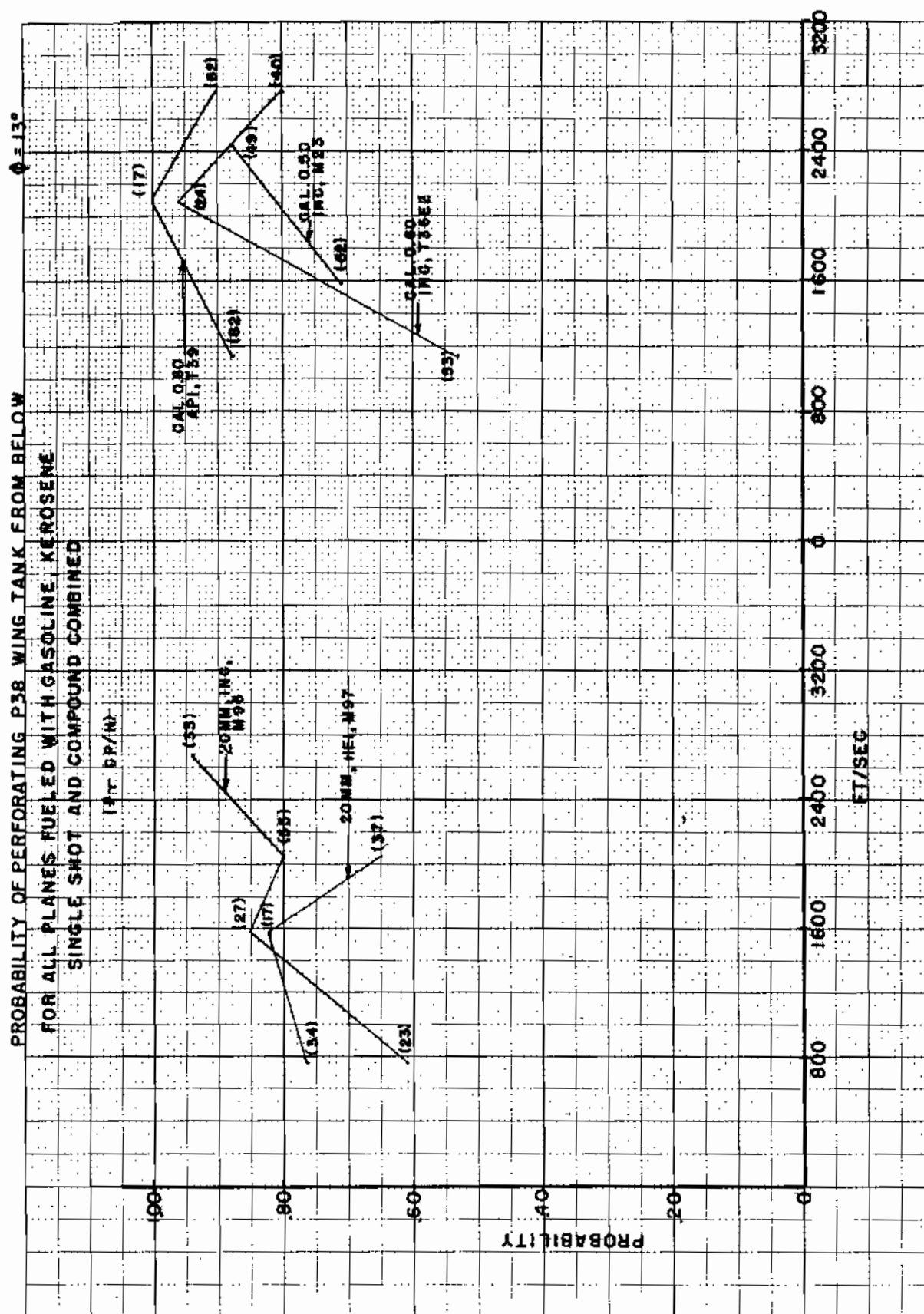


FIG. 4



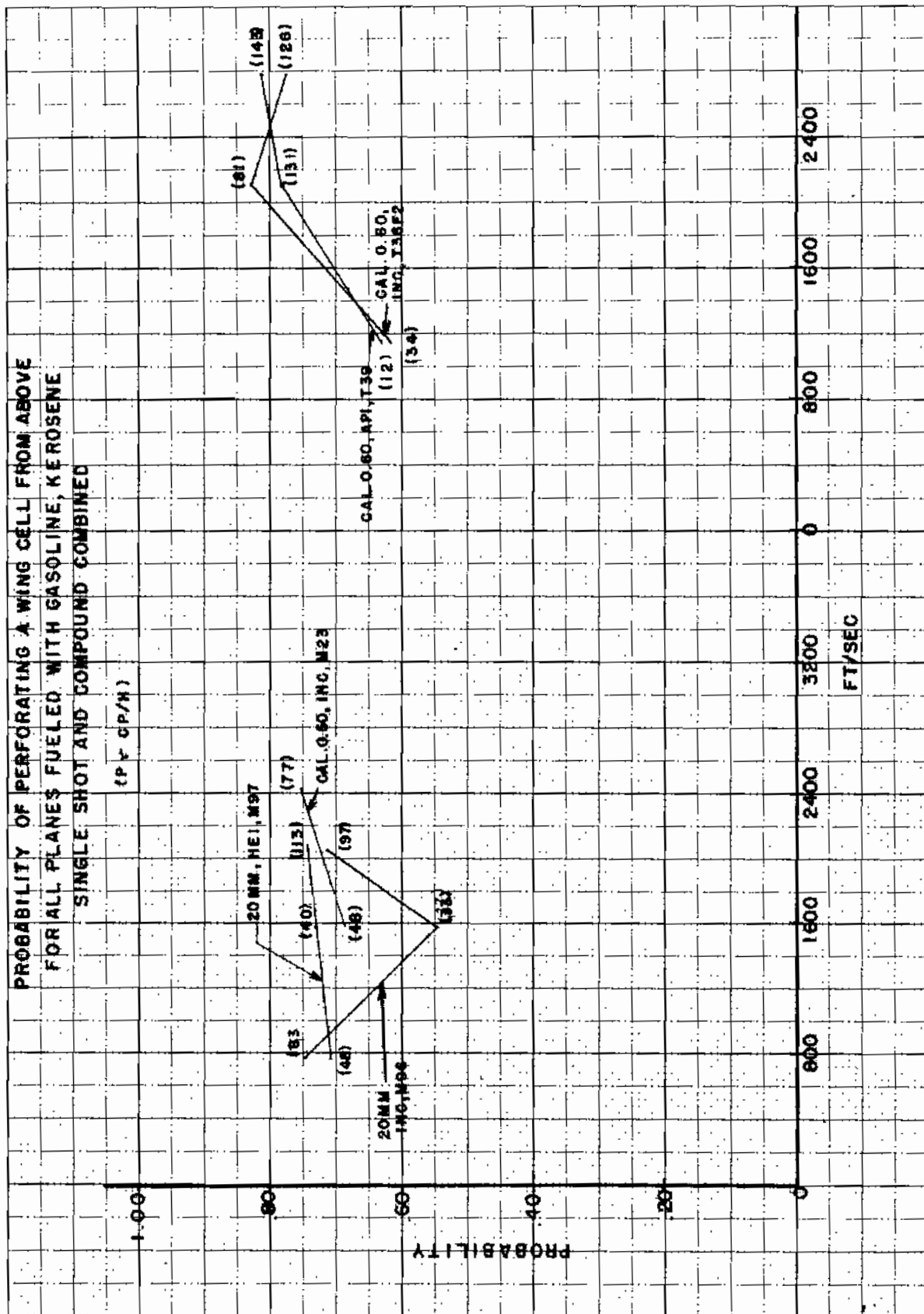


FIG. 6

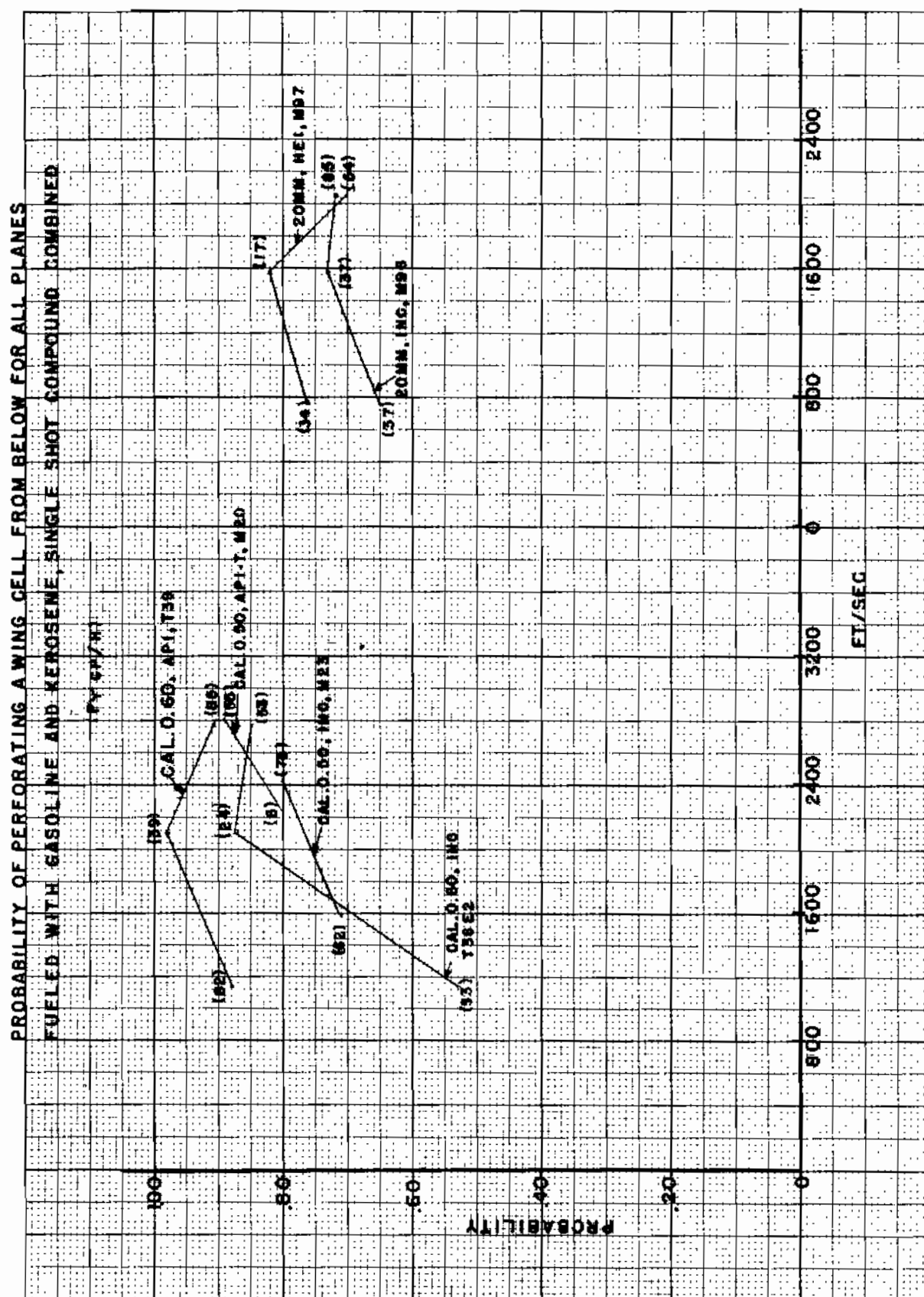


FIG. 7

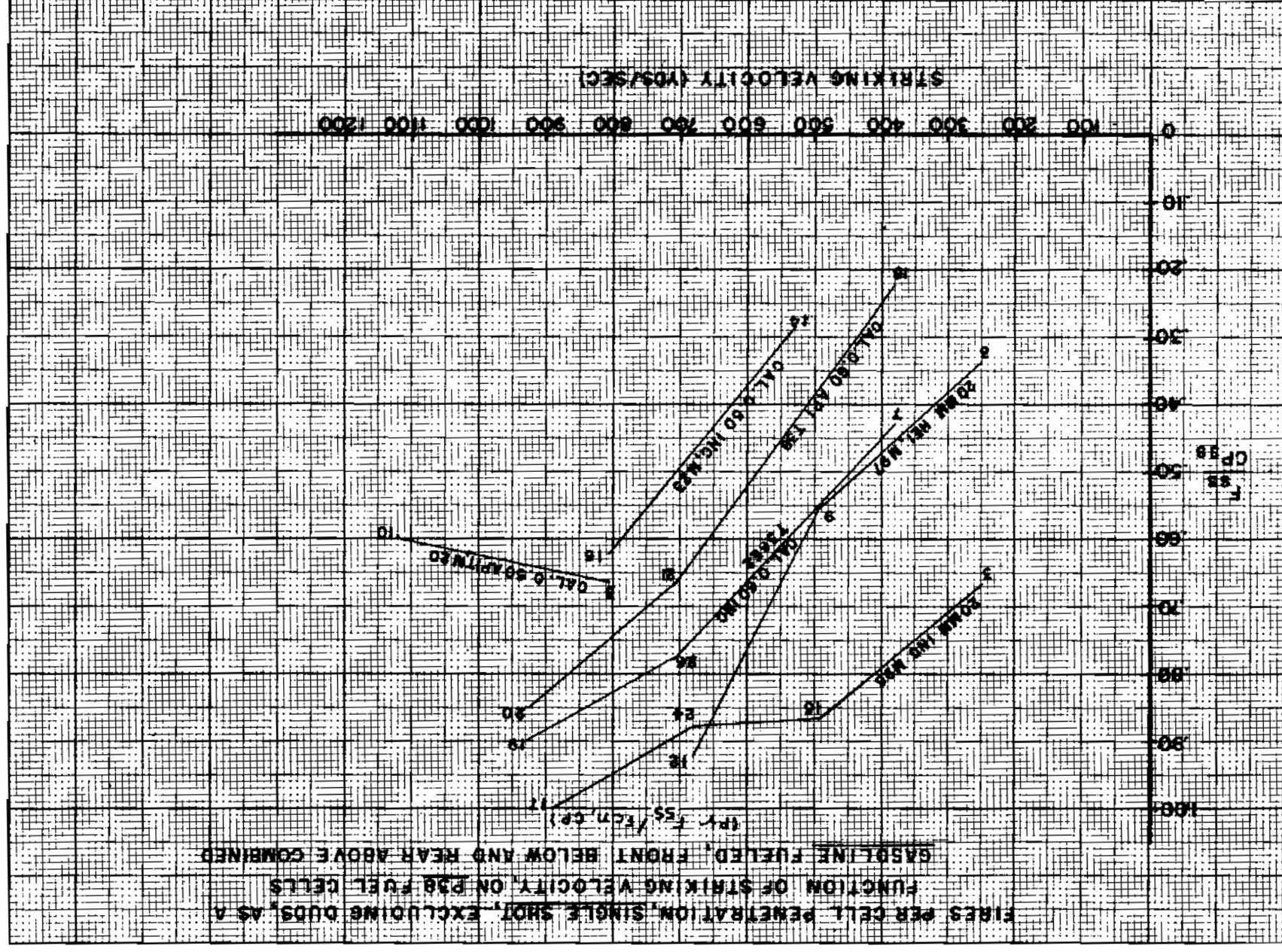


FIG. 8

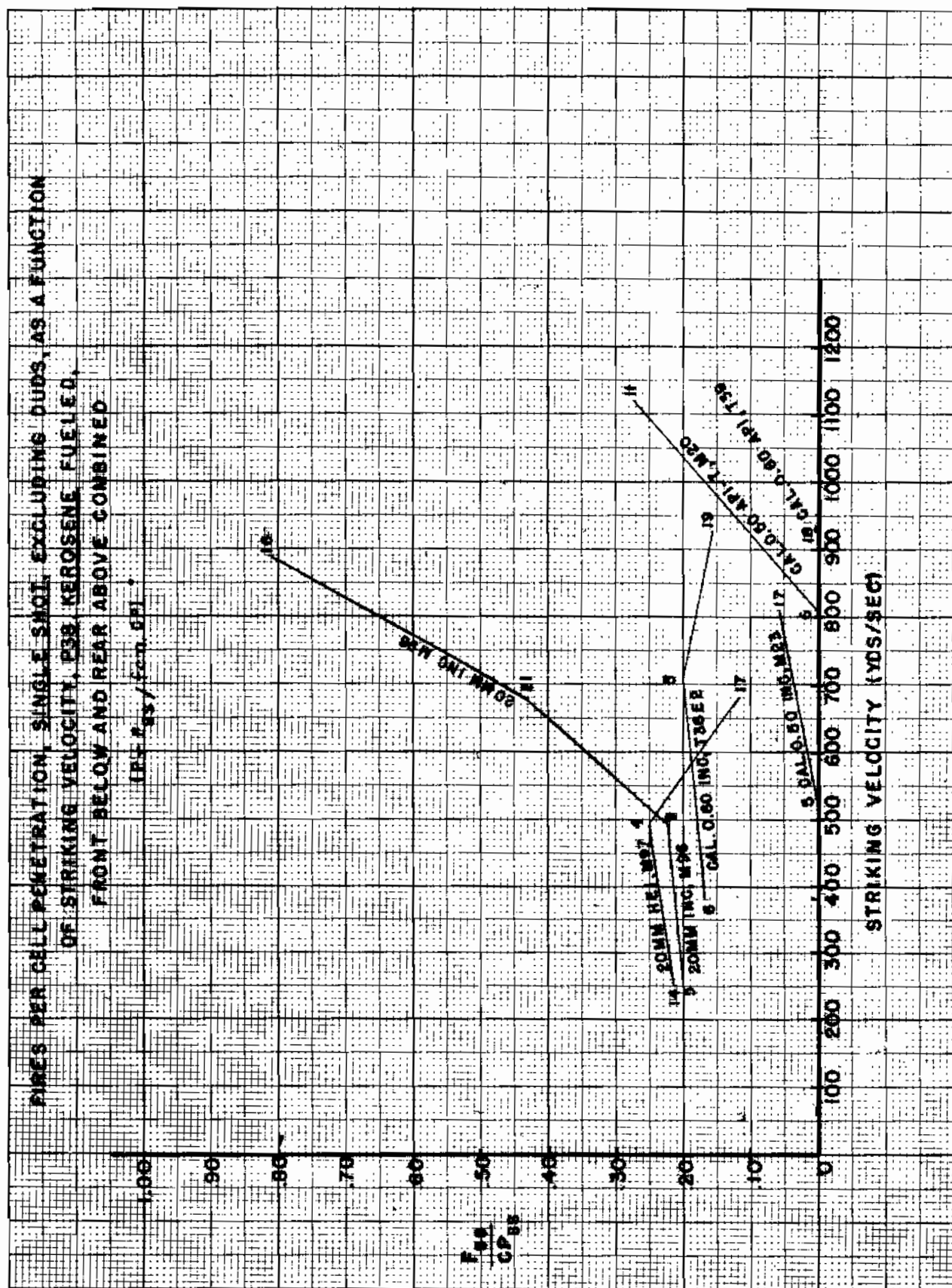


FIG.9

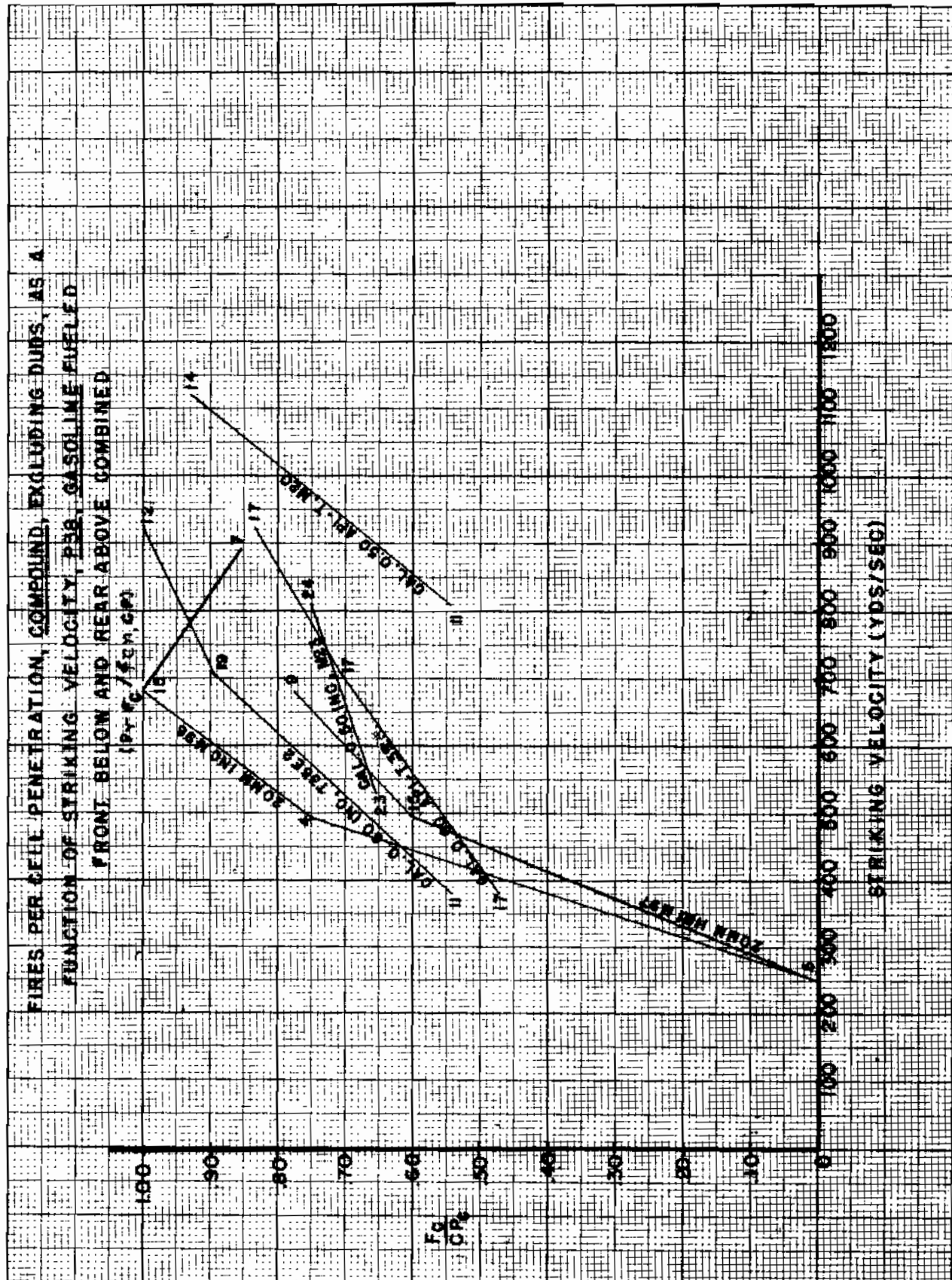


FIG.10

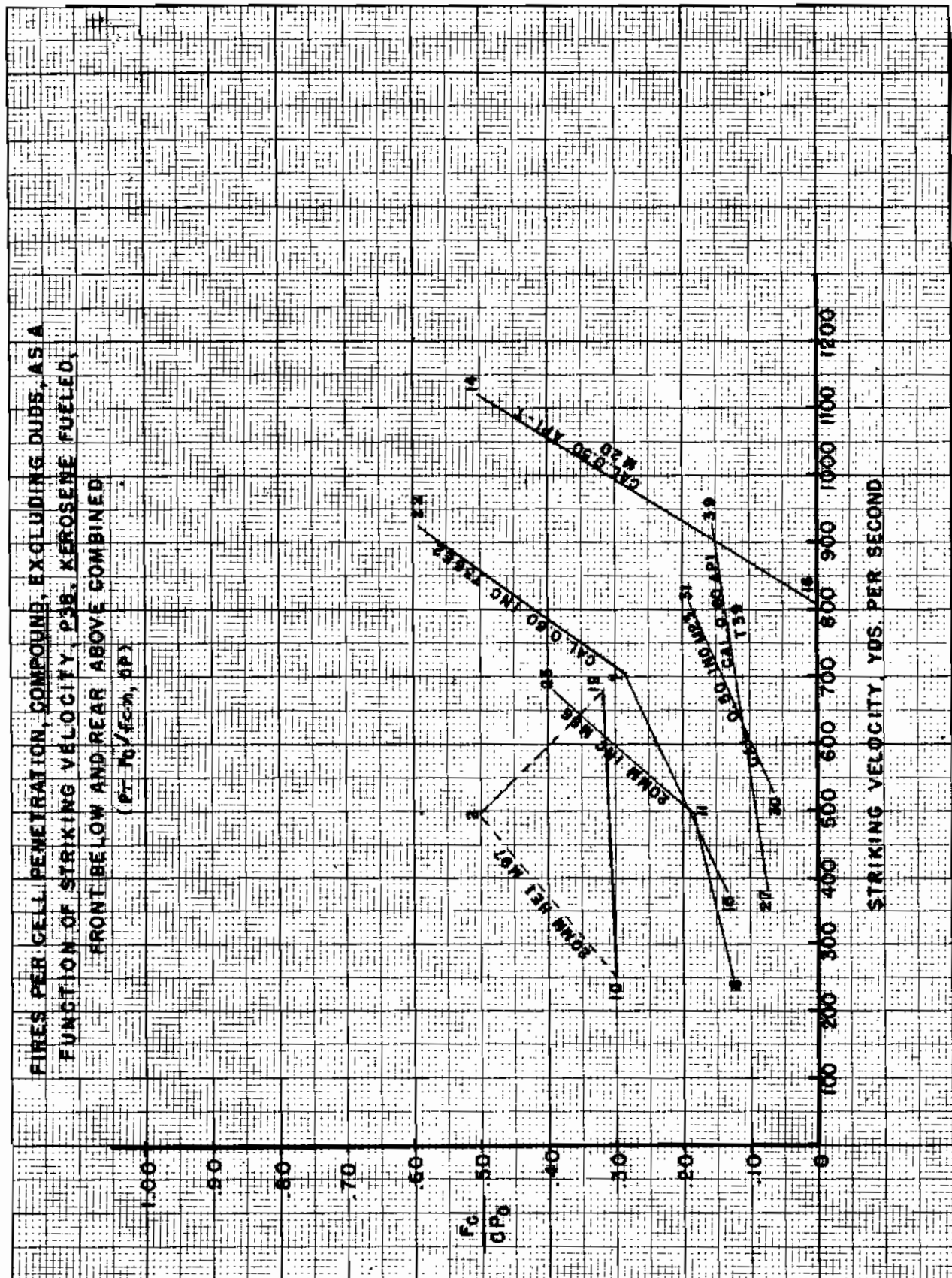


FIG. 11

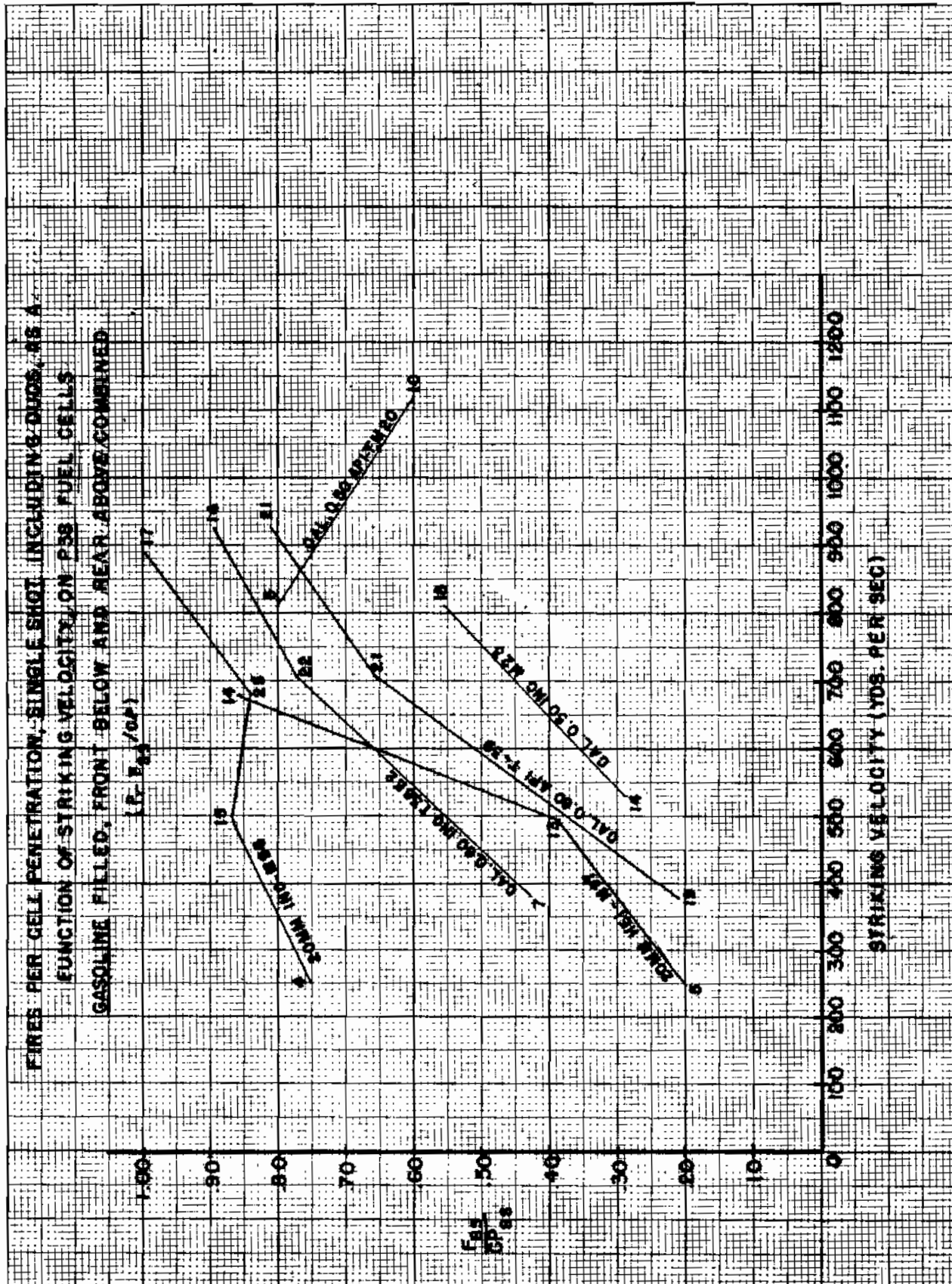


FIG. 12

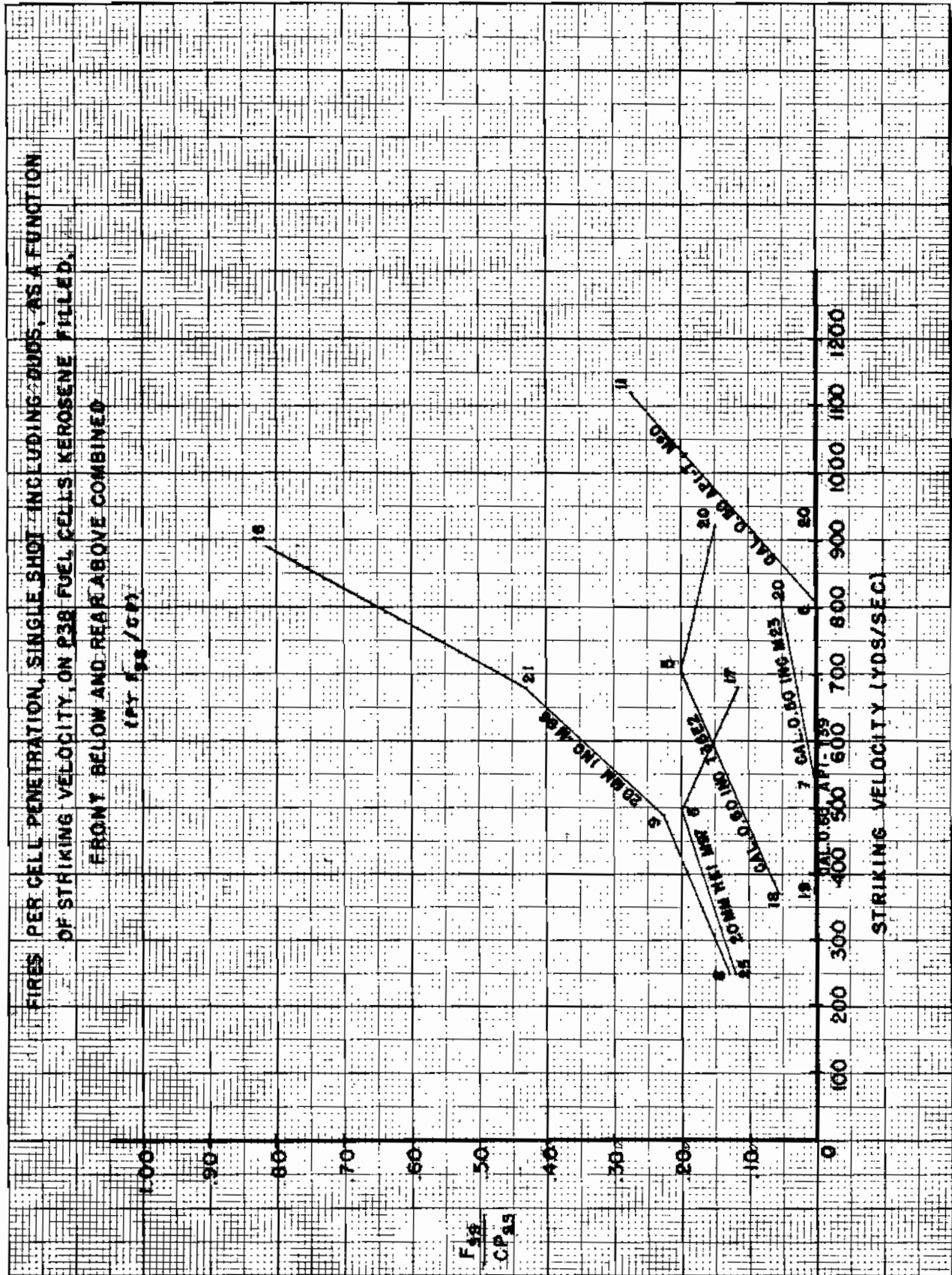


FIG. 13

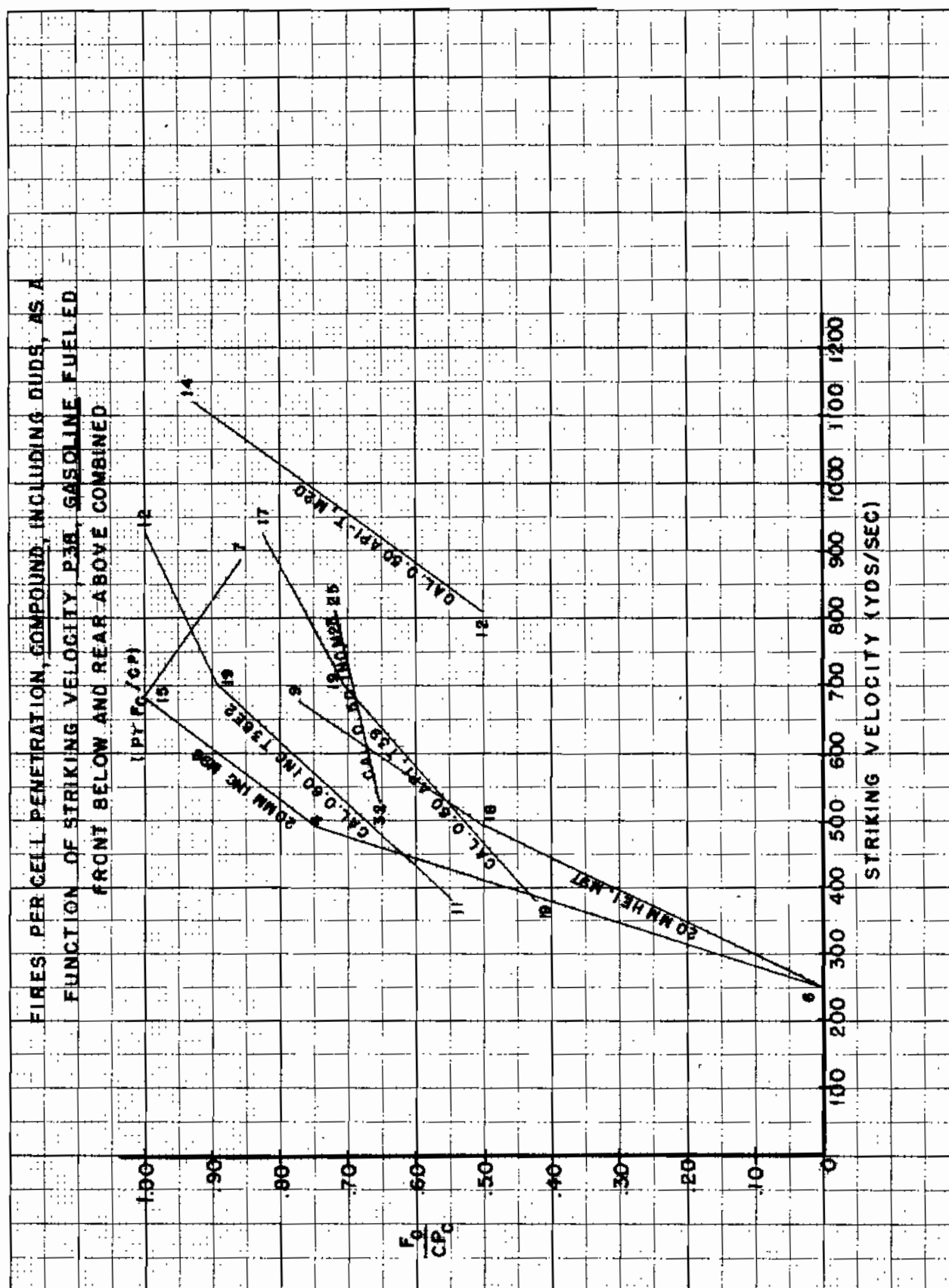


FIG. 14

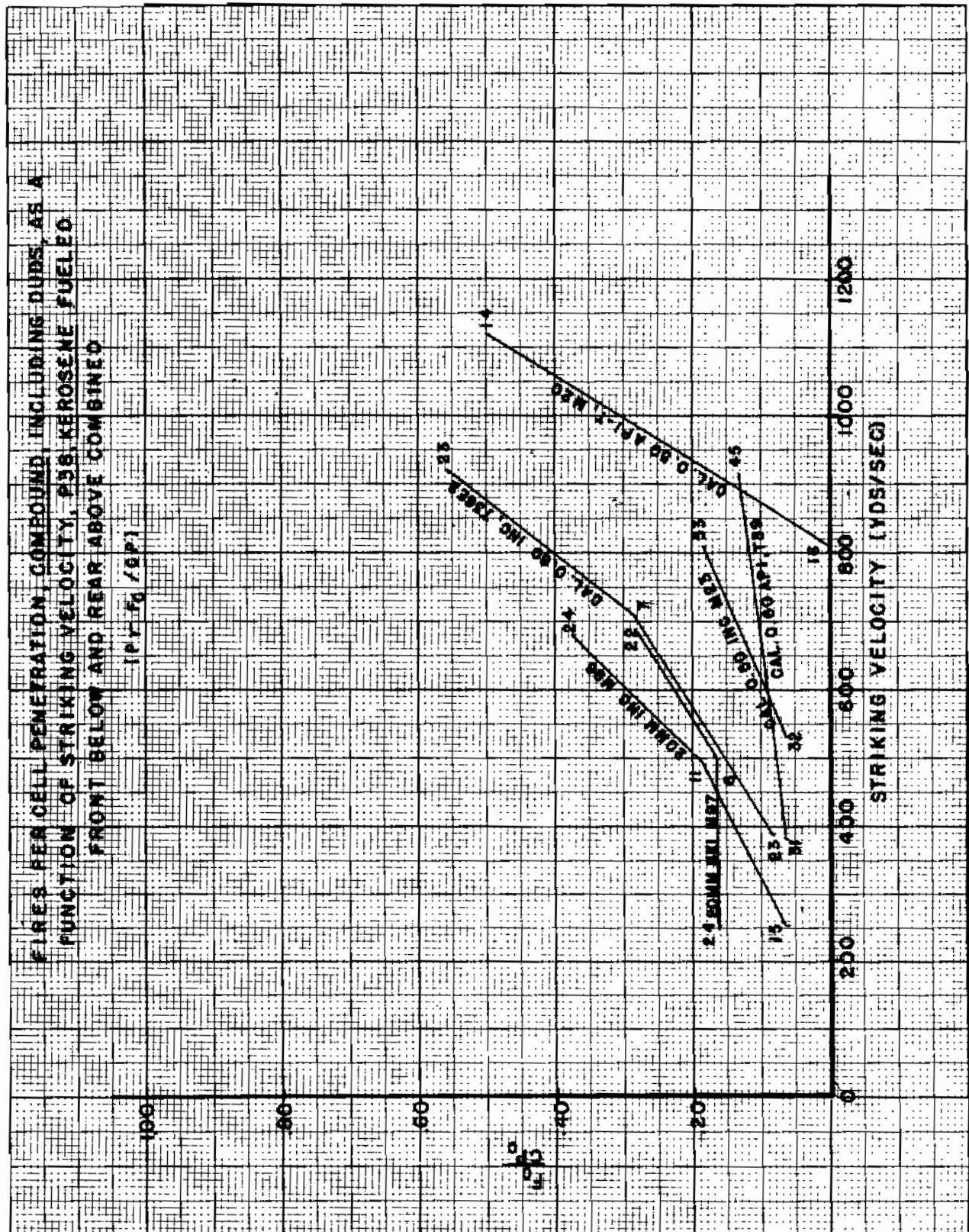


FIG. 15

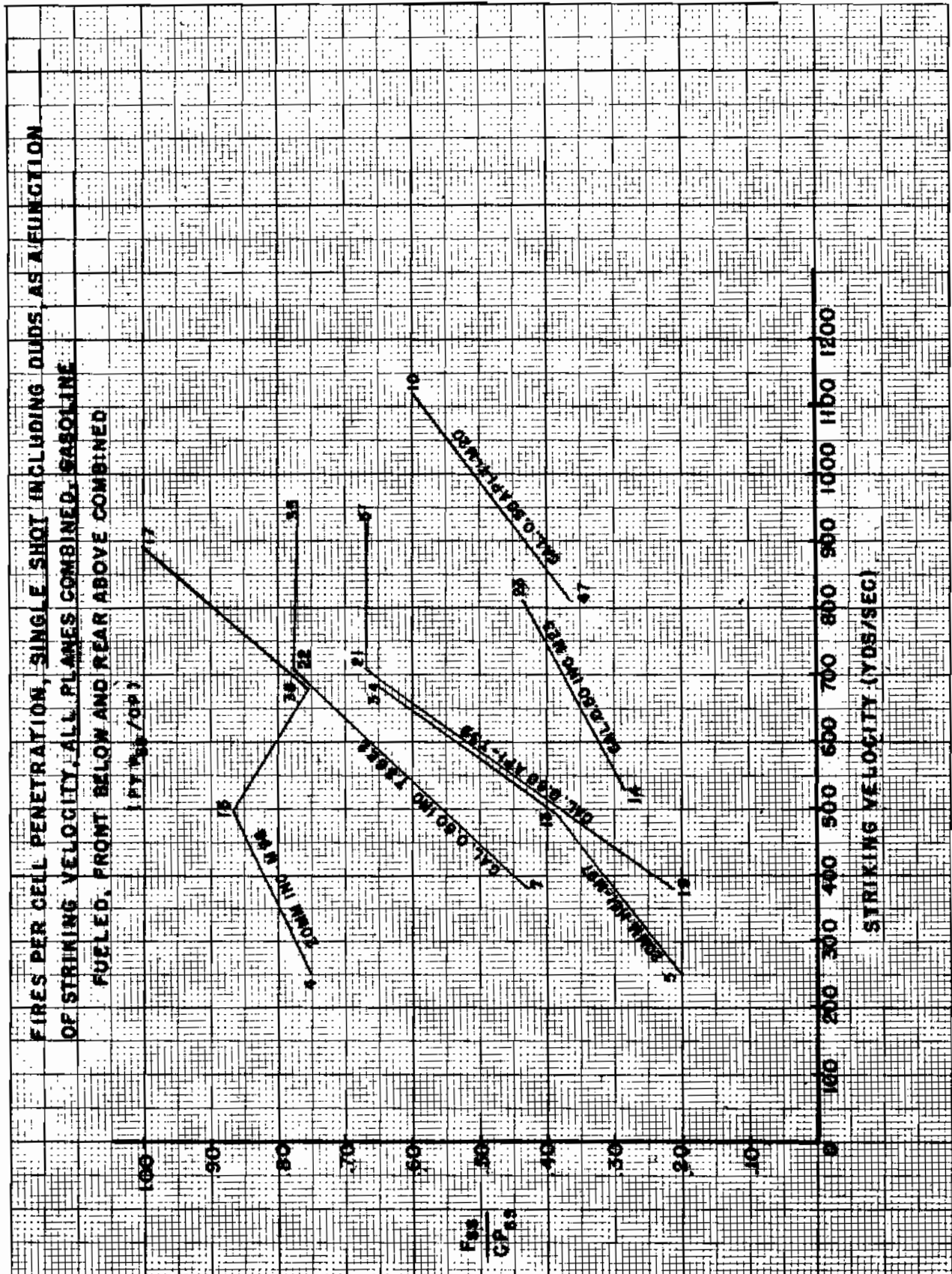
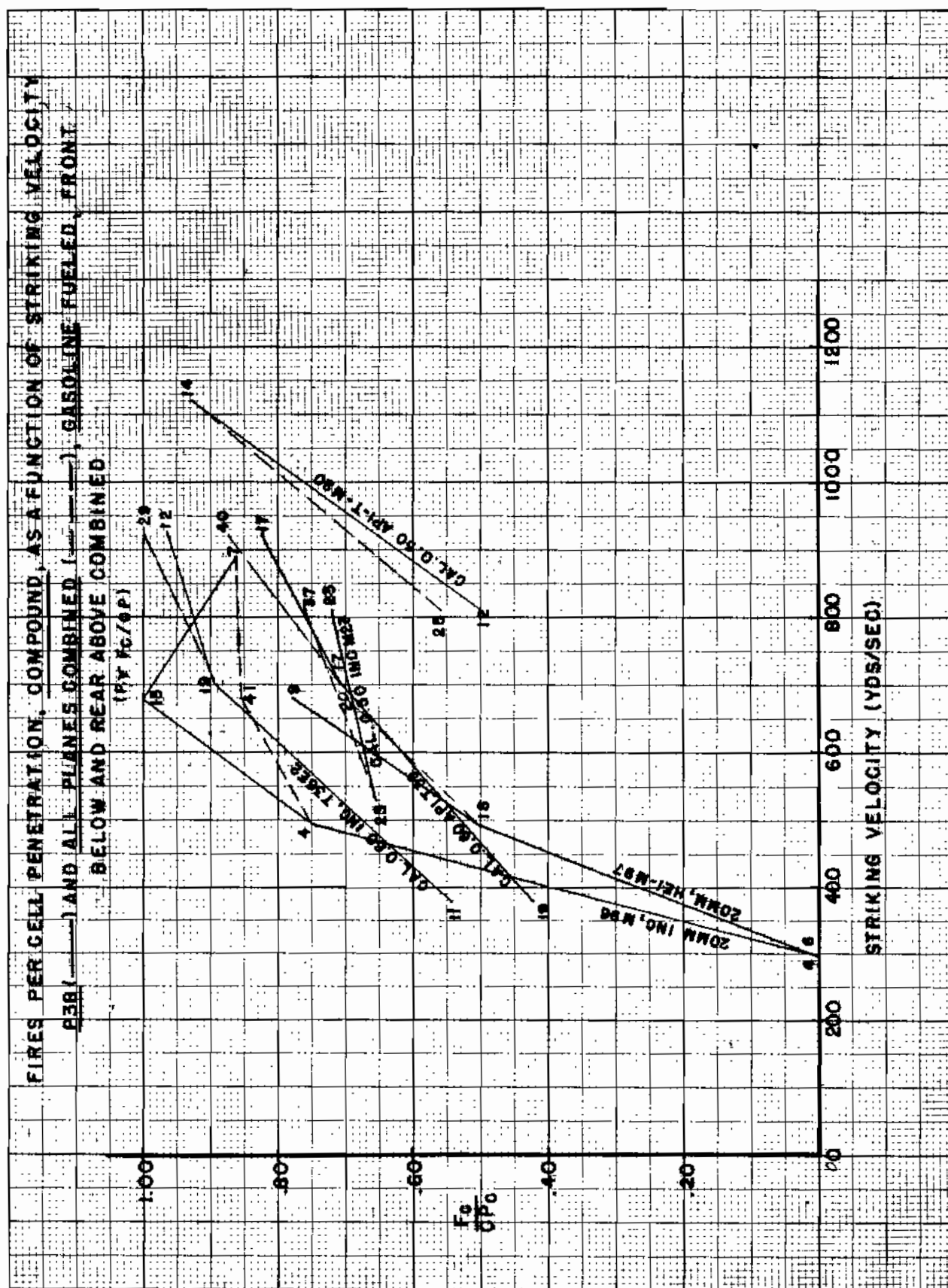


FIG. 16



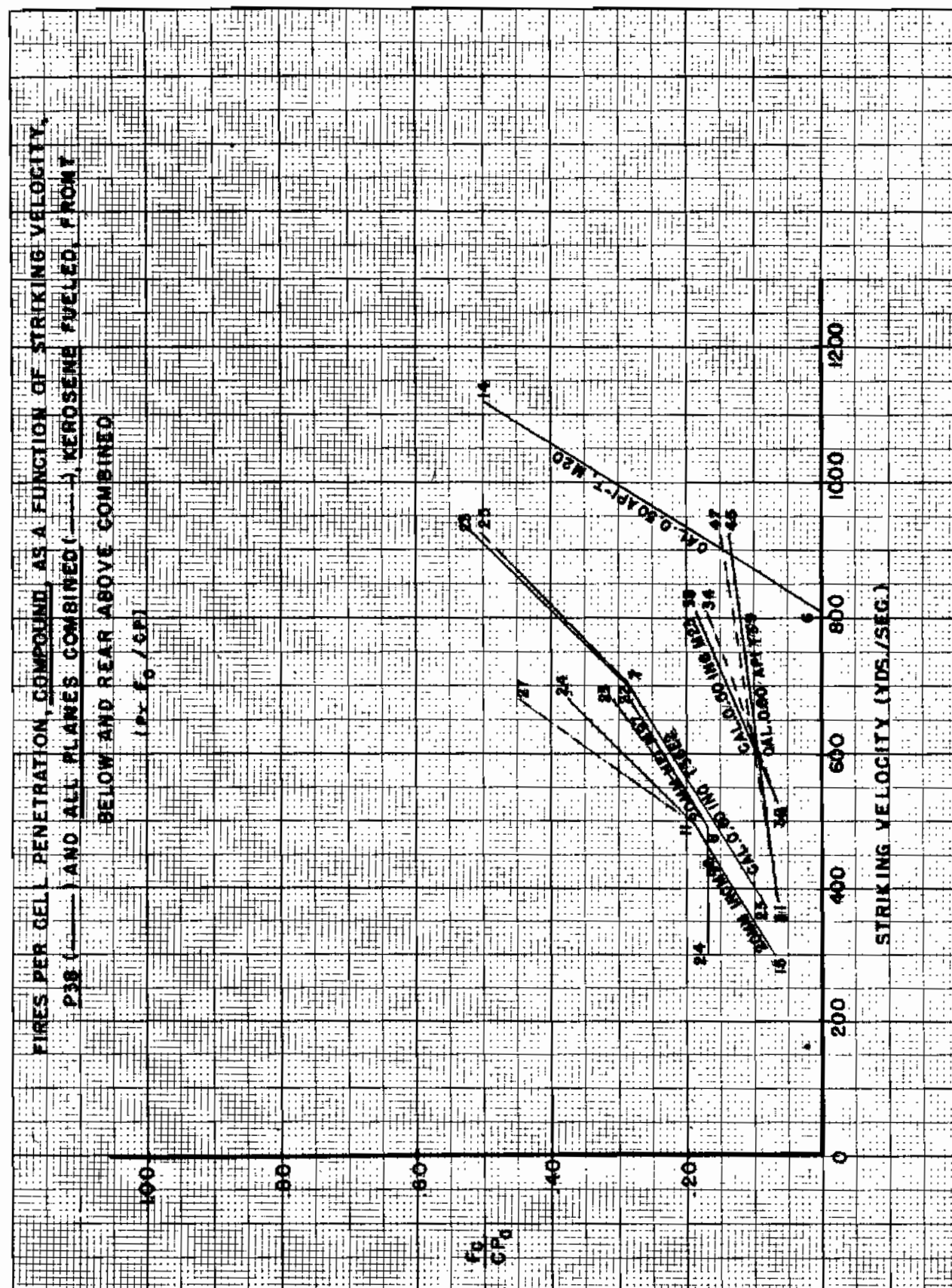
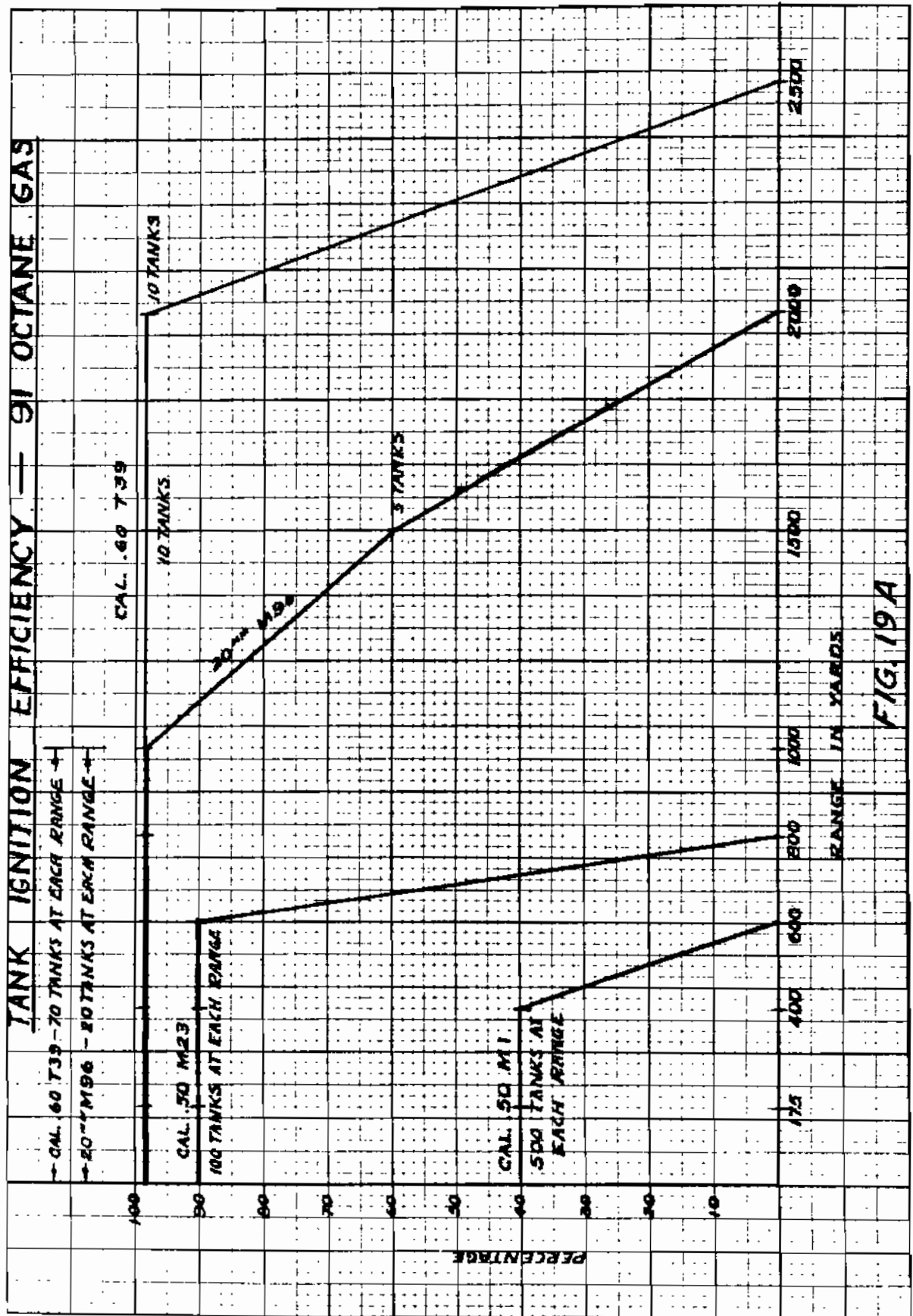


FIG. 19



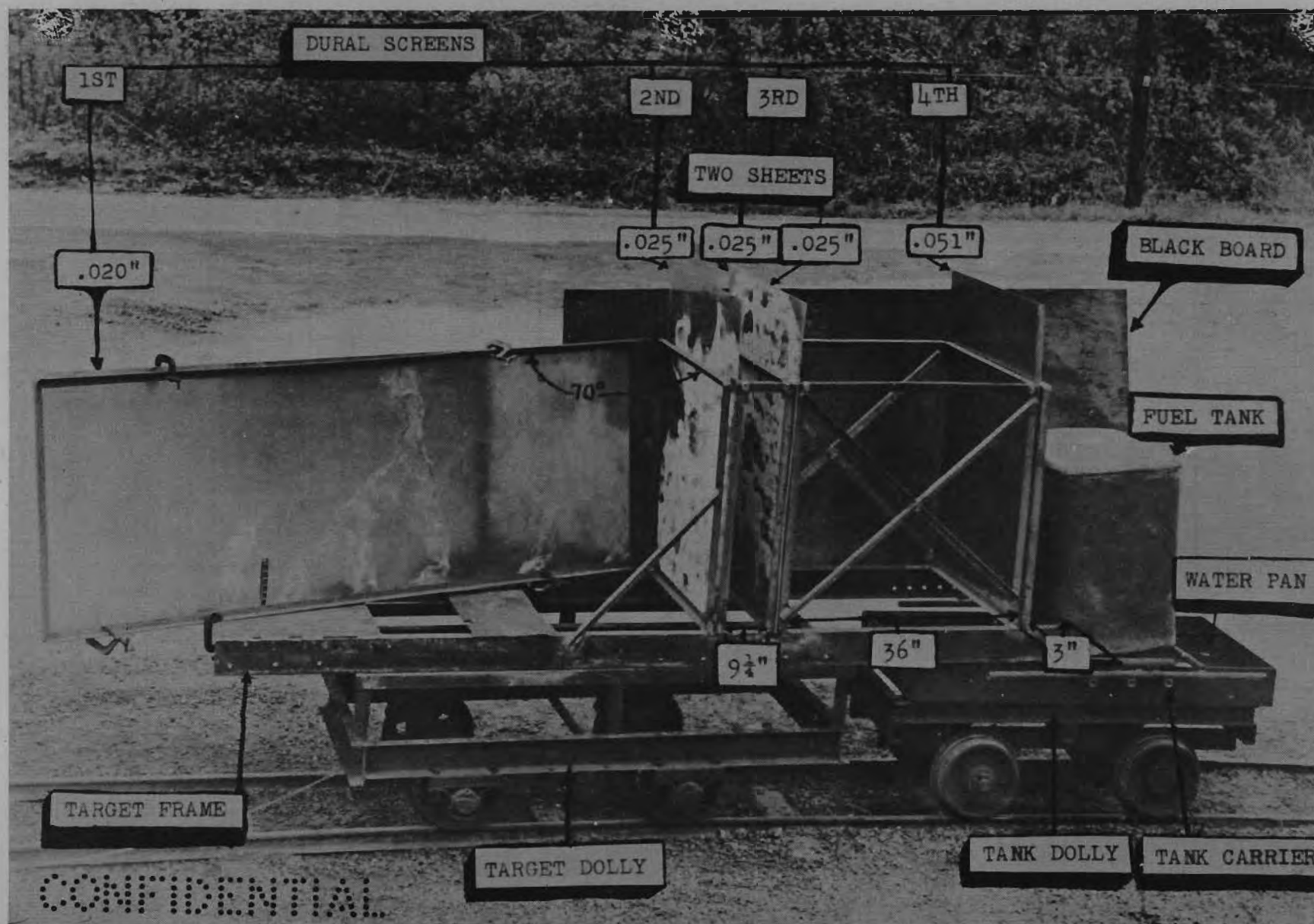
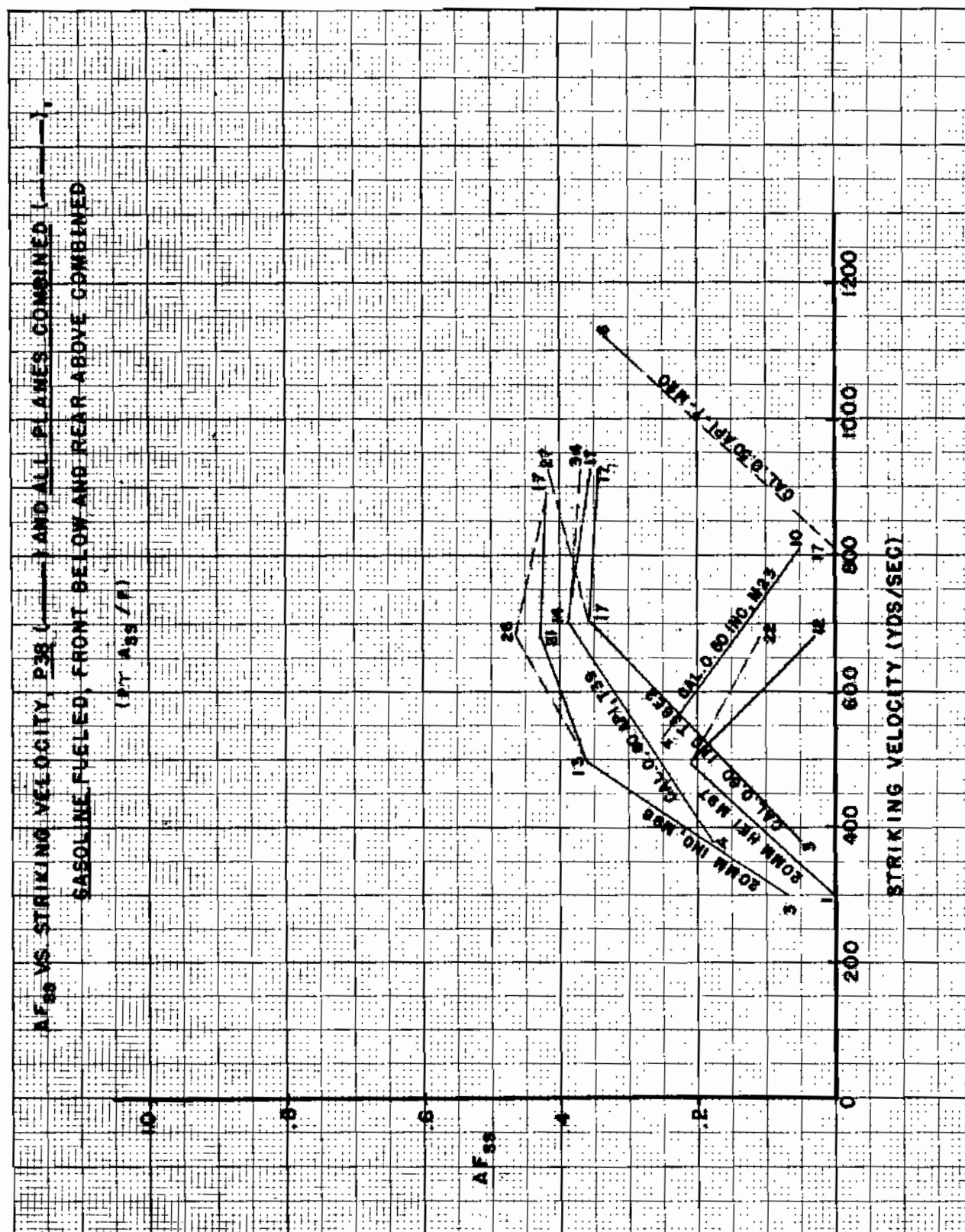


FIG. 19b. Replica Heinkel 111 target frame, filled with dural and a fuel test tank in position. Dural Screen #3 has 2 sheets .025".



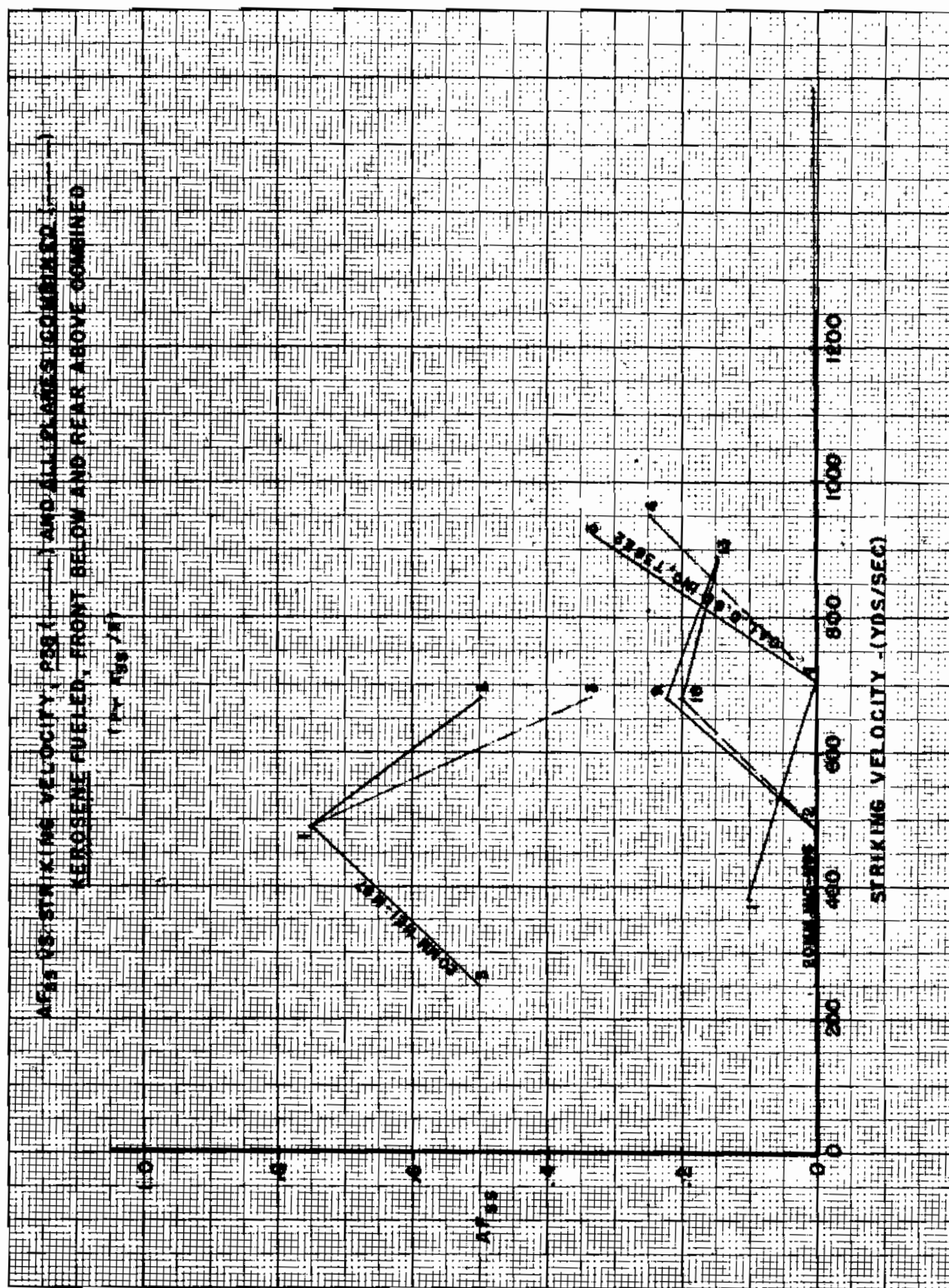


FIG.21

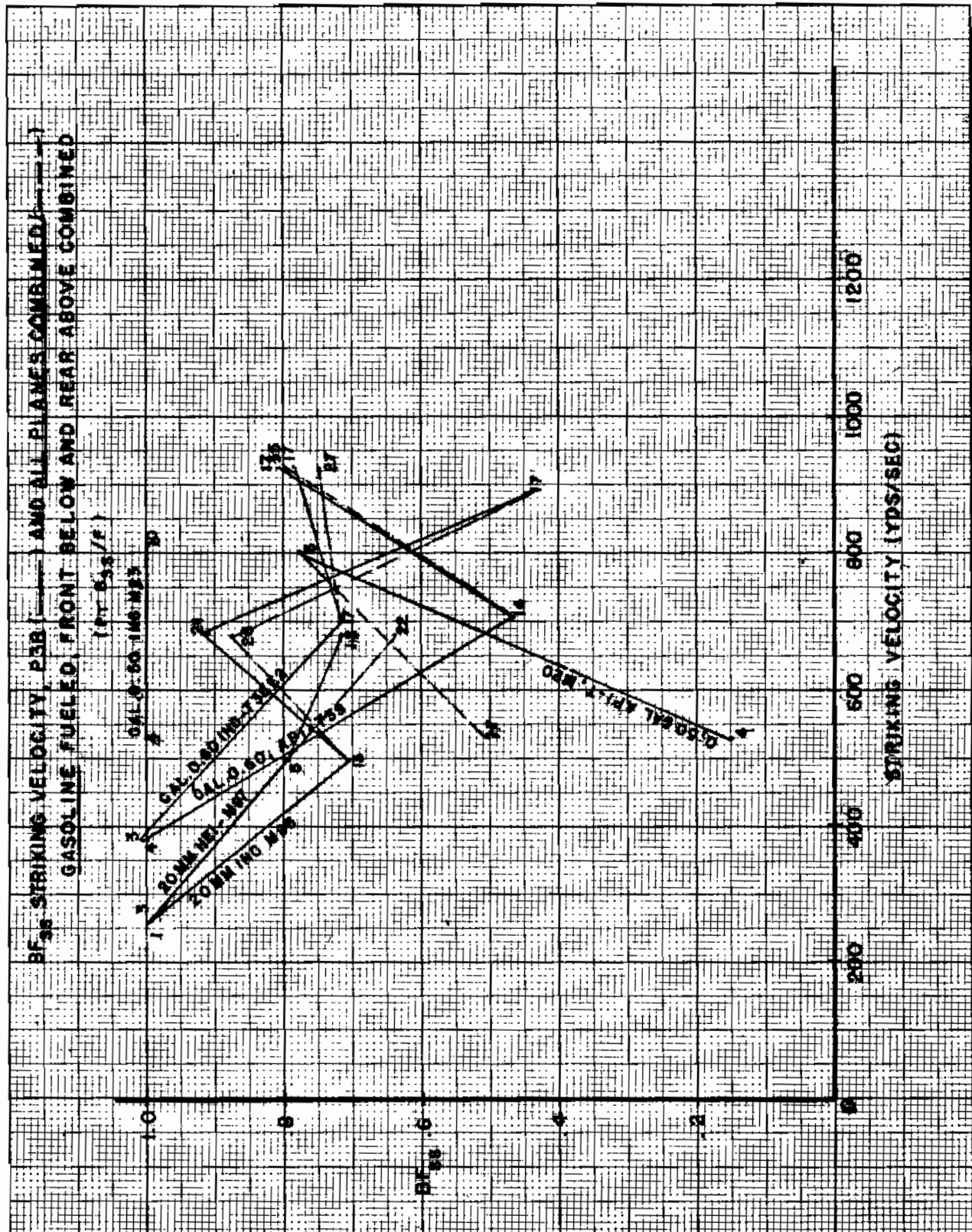


FIG. 22

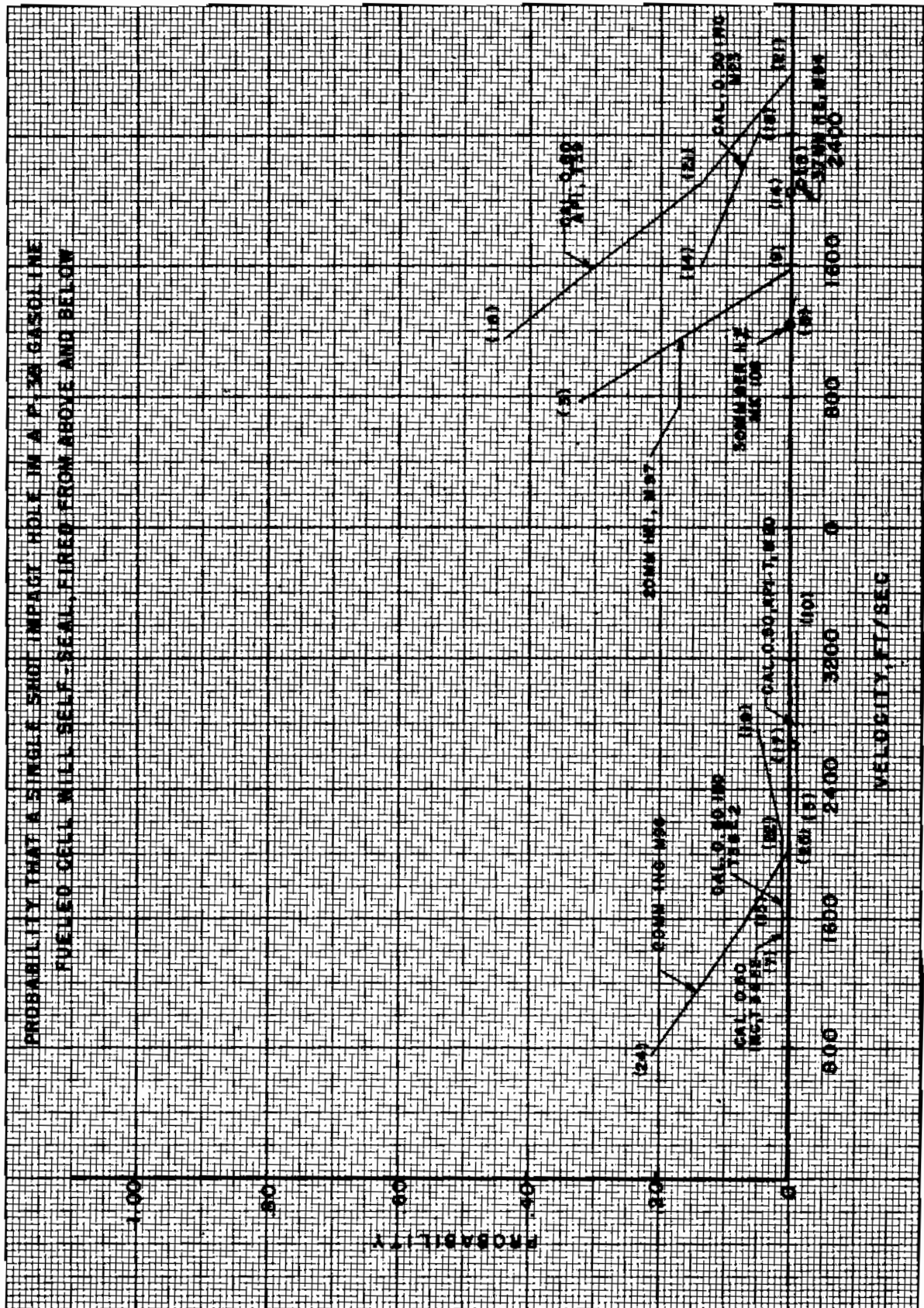


FIG. 24

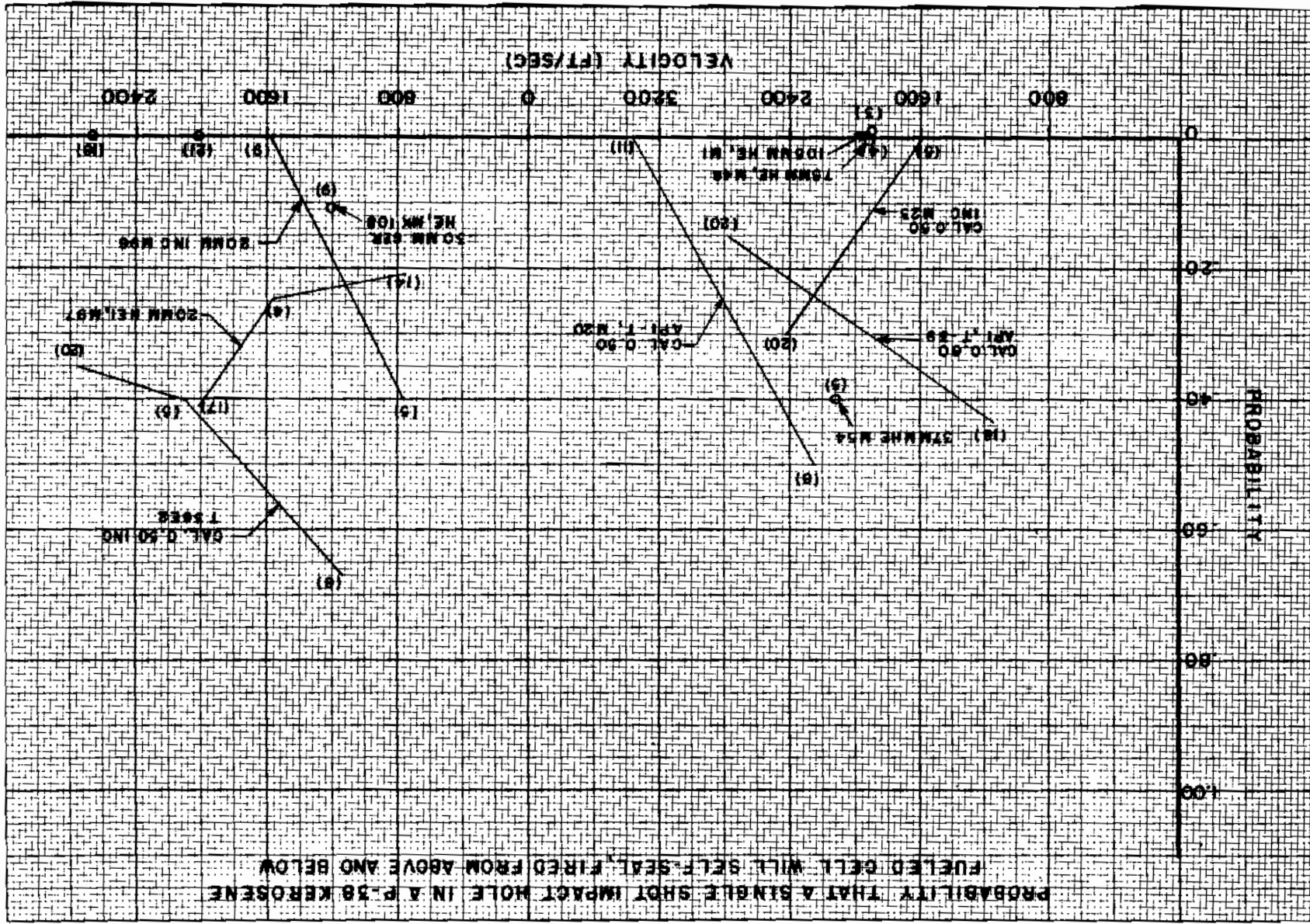


FIG. 25

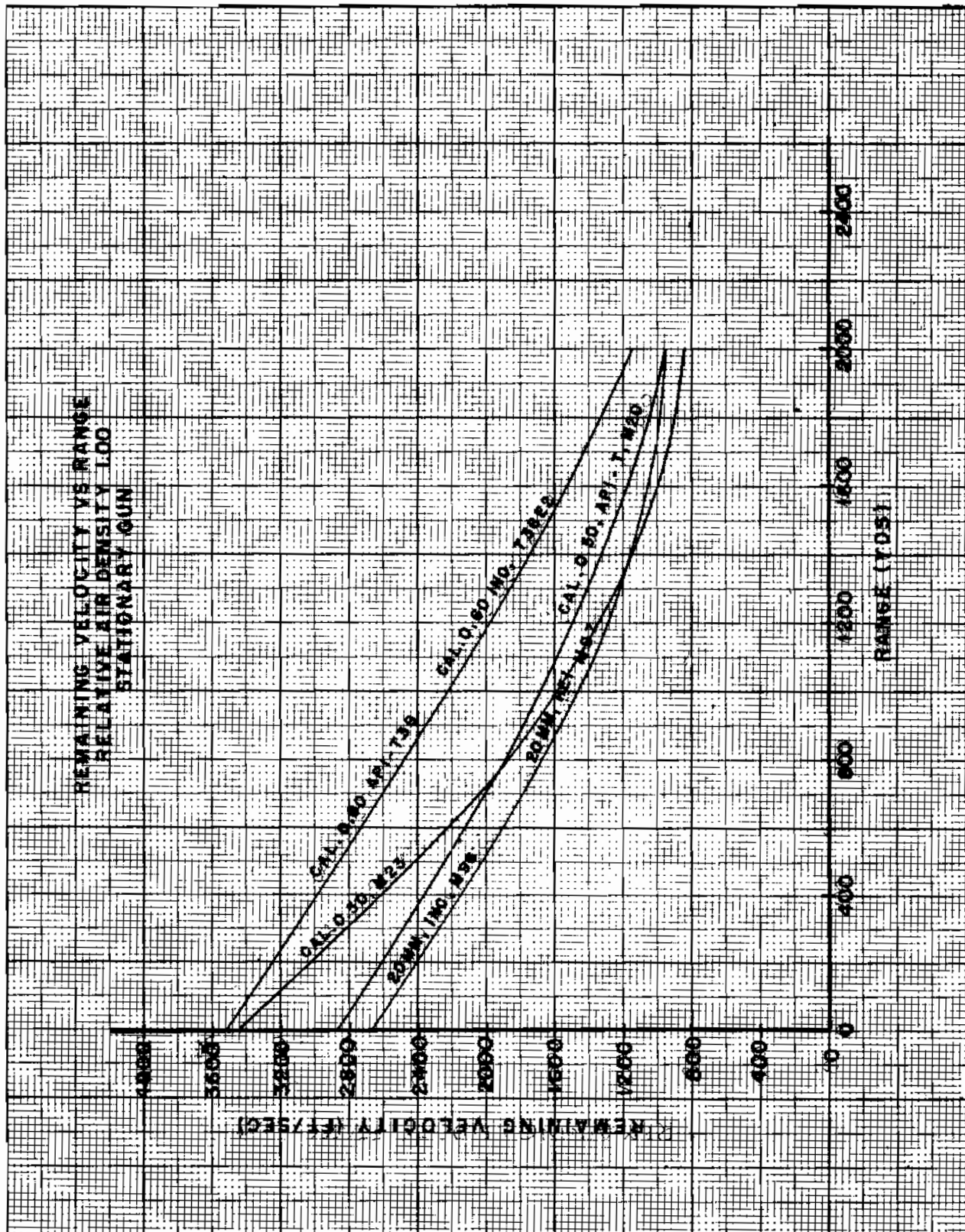


FIG. 26A

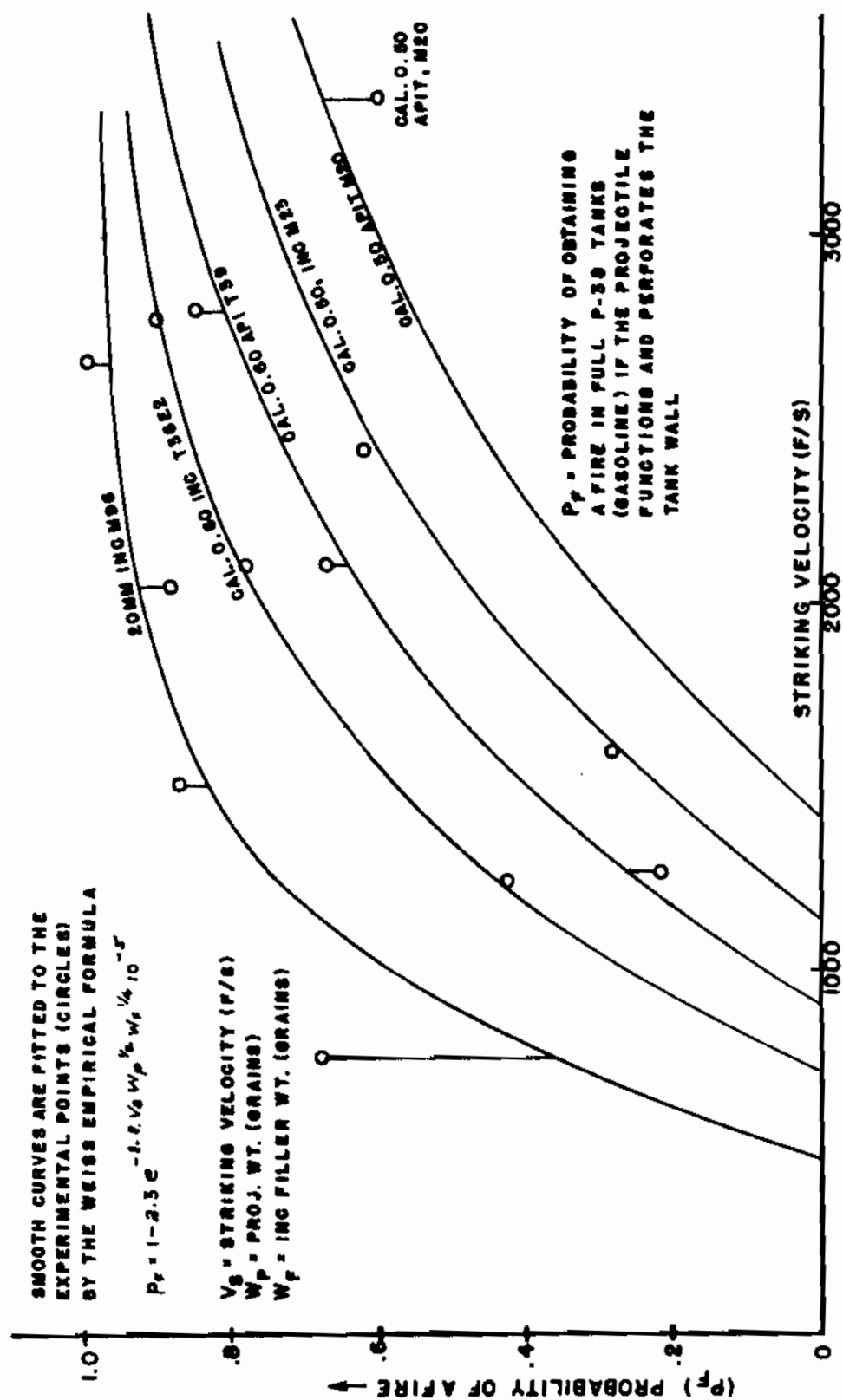


FIG 26B

10 JUNE 1946
TERM. BALL. LAB.
WPNS. EFFECT. BRANCH
BALL. RES. LAB., APO.

TAB E I (Continued)

C. Compound Shot P38 Fuel Cell Ignition and Leakage for Firings from Front, Below $\theta = 20^\circ$, $\phi = 15^\circ$

Ammunition Caliber Type	Fuel Type	Striking Velocity ft./sec	Hits on Projected Area of Fuel Lines Includ. Exclud. Duds H _c	Perforations of Cell or Fuel Lines Includ. Exclud. Duds CP _c	Hits Causing Fires No Firings Leakage Includ. Exclud. Duds L _c	F _c H _c	Including Duds L _c H _c	I _c CP _c	F _c CP _c	Excluding Duds F _c CP _c	Average Assessments of Fire	
											$\frac{I_c}{F_c}$	$\frac{H_c}{G_c}$
Cal. 50 Inc. M23	Gasoline	8430	11	9	6	545	273	500	567	567	0.0	0.0
		1890	16	14	11	611	167	273	786	786	1.00	0.0
		2430	16	14	0	000	230	285	000	000	0.0	0.0
		1590	31	20	2	065	516	600	100	100	0.02	0.0
Cal. 50 API-T, M20	Gasoline	3360	14	14	13	989	071	1000	929	929	0.56	0.44
		3360	14	14	7	560	560	1000	500	500	1.00	0.79
		2700	14	11	9	643	071	786	818	818	0.44	0.44
		2700	10	10	6	000	000	1000	000	000	0.0	0.0
Cal. 60 API, T39	Gasoline	2100	15	13	8	353	066	867	076	076	0.31	0.22
		1140	25	25	22	180	180	1000	180	180	0.33	0.33
		2770	25	25	22	180	180	1000	180	180	0.33	0.33
		1140	34	29	2	059	411	685	069	069	0.0	0.0
Cal. 60 Inc. T36E2	Gasoline	2700	4	3	3	750	000	750	000	000	0.0	0.0
		2100	9	9	0	1000	000	1000	1000	1000	0.0	0.0
		1140	8	4	2	250	250	500	250	250	0.0	0.0
		2770	14	11	6	428	428	786	545	545	0.17	0.17
20mm HEI, M97	Kerosene	1140	25	16	1	040	040	640	065	065	0.0	0.0
		2050	2	2	2	1000	1000	1000	1000	1000	0.0	0.0
		1590	11	8	4	344	500	727	263	263	0.0	0.0
		2050	25	11	3	130	398	478	273	273	0.0	0.0
20mm Inc. M66	Gasoline	2870	7	7	6	887	143	1000	143	143	0.0	0.0
		2050	9	5	0	000	000	000	000	000	0.0	0.0
		1590	1	1	0	100	100	100	100	100	0.0	0.0
		760	41	26	17	243	122	635	192	192	0.0	0.0
20mm Inc. M66	Kerosene	2870	0	0	0	000	000	000	000	000	0.0	0.0
		2050	16	12	8	500	500	750	533	533	0.0	0.0
		1590	11	7	1	091	857	686	143	143	0.0	0.0
		760	14	10	6	000	285	714	400	400	0.0	0.0

D. Compound Shot P38 Fuel Cell Ignition and Leakage for Firings from Rear, Above $\theta = 20^\circ$, $\phi = 15^\circ$

Ammunition Caliber Type	Fuel Type	Striking Velocity ft./sec	Hits on Projected Area of Fuel Lines Includ. Exclud. Duds H _c	Perforations of Cell or Fuel Lines Includ. Exclud. Duds CP _c	Hits Causing Fires No Firings Leakage Includ. Exclud. Duds L _c	F _c H _c	Including Duds L _c H _c	I _c CP _c	F _c CP _c	Excluding Duds F _c CP _c	Average Assessments of Fire	
											$\frac{I_c}{F_c}$	$\frac{H_c}{G_c}$
Cal. 50 Inc. M23	Gasoline	2430	16	16	12	750	250	1000	250	250	0.0	0.0
		1590	16	16	4	230	212	563	558	444	0.0	0.0
		2430	19	18	6	316	474	1000	474	316	0.0	0.0
		1590	17	12	0	000	632	1000	000	000	0.0	0.0
Cal. 50 API-T, M20	Gasoline	2250	19	12	6	315	158	632	250	500	0.0	0.0
		2250	18	15	0	000	000	000	000	000	0.0	0.0
		2770	8	6	5	625	125	750	187	853	0.0	0.0
		2770	8	7	6	750	125	875	143	857	0.0	0.0
Cal. 60 API, T39	Gasoline	2100	7	6	0	000	429	858	500	000	0.0	0.0
		1140	25	20	3	120	120	900	150	150	0.0	0.0
		2770	25	20	3	120	120	900	150	150	0.0	0.0
		1140	4	2	0	000	000	000	000	000	0.0	0.0
Cal. 60 Inc. T36E2	Gasoline	2770	11	9	9	618	000	618	000	1000	0.0	0.0
		2100	11	10	8	727	000	909	000	900	0.0	0.0
		1140	10	7	4	400	400	700	571	571	0.0	0.0
		2770	14	12	7	500	214	857	250	585	0.0	0.0
20mm HEI, M97	Kerosene	2100	11	7	2	182	435	636	714	287	0.0	0.0
		1140	9	7	1	091	564	592	145	333	0.0	0.0
		2050	16	10	10	625	000	625	000	1000	0.0	0.0
		1590	5	3	2	867	000	1000	867	867	0.0	0.0
20mm Inc. M96	Kerosene	740	5	4	0	000	400	800	000	000	0.0	0.0
		2050	18	12	1	000	500	867	500	867	0.0	0.0
		1590	5	4	1	000	400	800	000	000	0.0	0.0
		740	6	5	2	187	533	633	400	500	0.0	0.0
30mm German HE, M108	Gasoline	1230	2	2	1	500	500	1000	500	500	0.0	0.0
		1230	11	7	7	636	000	636	000	1000	0.0	0.0
		2100	1	0	0	000	000	000	000	000	0.0	0.0
		2100	4	3	2	500	250	750	533	667	0.0	0.0
37mm HE, M54	Kerosene	1920	0	0	0	000	000	000	000	000	0.0	0.0
		1920	0	0	0	000	000	000	000	000	0.0	0.0
		1920	0	0	0	000	000	000	000	000	0.0	0.0
		1920	0	0	0	000	000	000	000	000	0.0	0.0
75mm HE, M49	Kerosene	1875	0	0	0	000	000	000	000	000	0.0	0.0
		1875	0	0	0	000	000	000	000	000	0.0	0.0
		1875	0	0	0	000	000	000	000	000	0.0	0.0
		1875	0	0	0	000	000	000	000	000	0.0	0.0

SUPPLEMENTARY TESTS

The principal "optimum caliber" tests are not of themselves sufficient if results are to be useful in the determination of the vulnerability of future aircraft to present or future types of ammunition. With regard to igniting aircraft fuel tanks, it is particularly important to obtain more basic data than could be obtained from observation of impacting projectiles on aircraft wings. The probability of igniting fuel tanks is sensitive to changes in type of incendiary functioning, fuzing of HE shell and environmental conditions. To obtain the necessary additional data, a number of supplementary tests have been designed with more limited and specialized objectives than the principal firings against aircraft. With these tests, it should be possible to observe more closely the behavior of the factors affecting ignition and to achieve greater control over significant variants. Some of these tests are briefly described in the following pages. It is hoped to present fully detailed reports after their completion.

INCENDIARY FUNCTIONING CHARACTERISTICS

There is in progress a series of firings of incendiary ammunition against various thicknesses of dural plate for impacts at several obliquities. The purpose of these tests is to observe (1) how the probability of functioning varies with type of projectile, thickness of dural plate, striking velocity, obliquity and the effect of spaced plate and (2) the characteristics of functioning, such as the position of initial flash after impact, and the length and the duration of flash.

Ultra-high speed motion pictures are used to give the duration of flash and still photographs yield details regarding the other characteristics of functioning. Figures 27 and 28 depict two typical observations.

There have been fired to date in this program, at normal obliquity, the Cal. 0.60 API, T39, Cal. 0.60 INC, T36E2, 20mm INC, M96 and the 20mm HEI, M97 against dural plate varying in thickness from .051" to .125" and at ranges of 175, 400, 800 and 1500 yards. These same projectiles have also been fired at 70° from normal against dural plate of .025" and .051" at ranges of 175 and 400 yards.

A short summary of preliminary results appears below.

Extreme Variations Observed in Incendiary Functioning Tests
Preliminary Results

Functioning Characteristic	Variation
Distance from target plate to first sign of flash	0 ft. to 10 ft.* 0 ft. to 10 ft.*
Distance from target plate to heart of flash	0 ft. to 14 ft.*
Length of flash	1 ft. to greater than field of view which was 16 ft.
Duration of flash when it did occur	2 to 56 milli- seconds.

*Some rounds did not begin to function until outside the field of view of the camera (16 ft.). One of these was visually estimated as functioning 35 feet behind the plate.

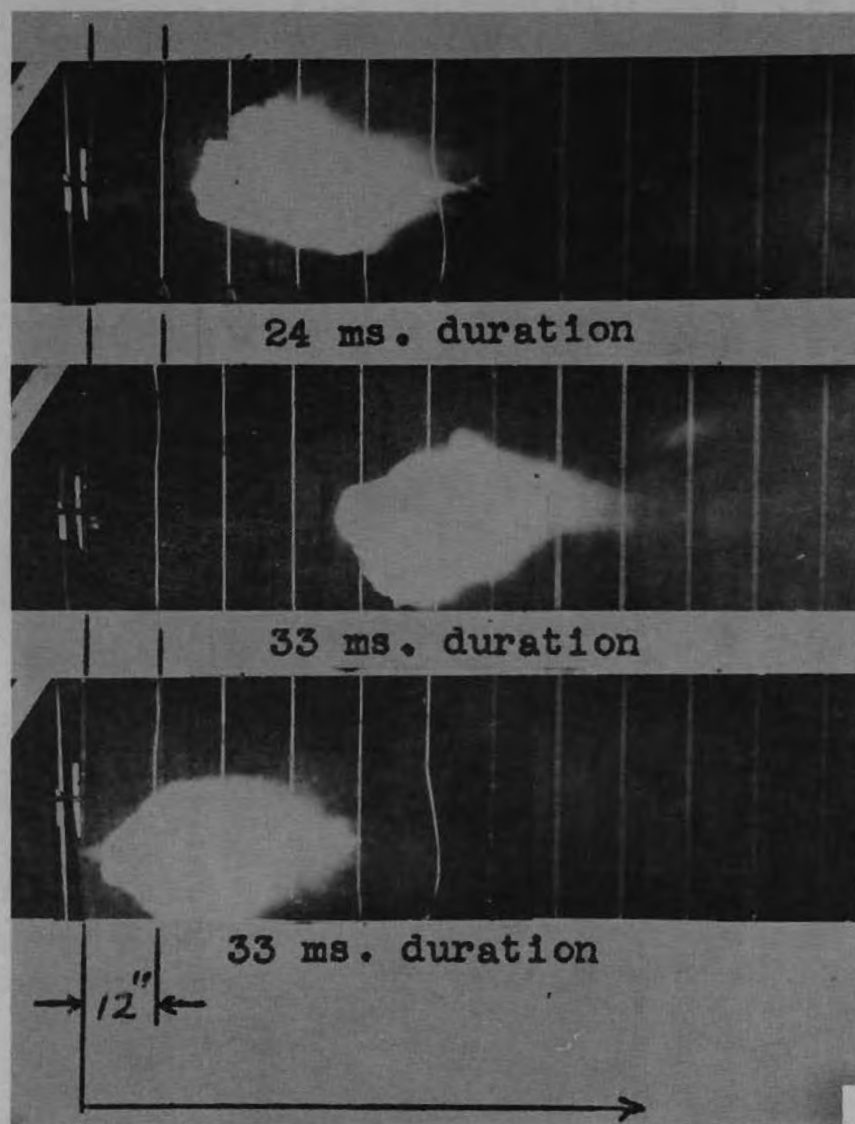


FIG. 27. Function of Ctg., API, Cal. .60, Lot FA 16, after impacting a .125" dural target set normal to the line of fire and at a range of 400 yards.

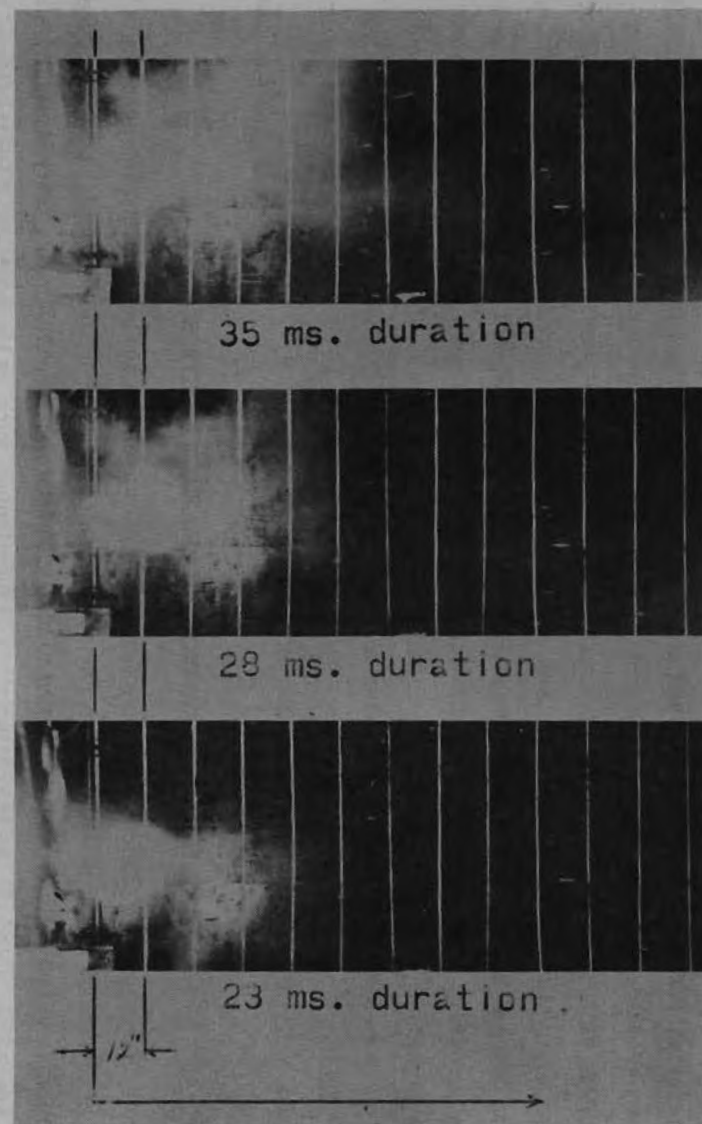


FIG. 28. Function of Ctg., API, Cal. .60, Lot FA 16, after impacting a .125" dural target set normal to the line of fire and at a range of 800 yards.

The importance of the results of these tests on incendiary functioning characteristics cannot be overestimated.

On the one hand, when coupled with tests on fuel spray emergence from impact holes, they provide the designer of incendiary ammunition with the data he needs to understand the variability in the fuel cell igniting efficiency of various types of incendiary bullets and a means for prediction of performance before costly tests against fuel cells are performed. Also, tests such as these may reveal much more concerning the probable effectiveness of a lot of incendiary ammunition up for acceptance, than firings against replica fuel cell targets. That this has been a major concern of the Ordnance Department during the war is evident from the important tests conducted at Frankford Arsenal and at Aberdeen to study the mechanics of ignition and incendiary functioning.^{1, 2, 3}

On the other hand, these results are highly significant to the designer of aircraft fuel installations. For he may take advantage of this variability in incendiary functioning and arrange the fuel tanks so that, under most conditions of attack, the functioning will occur within the tank rather than between the skin and the tank. Some distance between skin and tank is advisable so that petalling of the skin around the impact hole is kept from holding open a hole in the tank and preventing sealing. It is unfortunate that the prevention of ignition of fuel cells by fragment impact indicates a need for greater distance between skin and tank. Hence, a choice of design will thus depend to a great extent on the type of attack expected. Bombers are more likely to be subject to fragment impacts than fighters. The degree of this difference may be indicated by intelligence reports and is a subject for a thorough study of its own.

FUEL TANK SPRAY STUDIES

Ignition of fuel tanks by incendiary bullet impacts below the fuel level occurs on the outside of the tank where the vapor-air mixture is lean enough for combustion. The incendiary projectile will not, with present incendiaries, cause a kill by ignition within the fuel tank below the fuel level. The incendiary must maintain temperatures above the ignition temperature of the combustible vapor-air mixture resulting on the outside of the tank as a result of the perforation of the tank wall. This ignition temperature must be maintained long enough to ignite the fuel spray emerging from the impact hole. The seriousness of the resulting fire depends thereafter on the amount of fuel feeding the fire and hence on the degree of self-sealing. Often the initial ignition burns or chars the tank material to such an extent as to defeat the self-sealing of the tank. The study of the duration of incendiary flashes (and also flashes resulting from fragment impacts) should therefore be supplemented by the study of spray emission from fuel tanks after impact.

¹FA R-567 "High Speed Motion Picture Study of Ignition of German Type Self-Sealing Tanks Placed to Rear of Heinkel Replica Target", E. R. Thilo, Nov. 1944.

²APG FR S-39192 - O.P. 5374, "To Investigate the Application of High Speed Motion Pictures to the Study of Flash and Tank Ignition Characteristics of Cartridge, Incendiary, Cal. .50 M1.

³The bibliography and description of incendiary research and development contained in the Ordnance Department Record of Research and Development in Small Arms Ammunition loc. cit.

The fact that fuel tank ignition usually occurs as a result of ignition of the vapor air mixture on the outside of the tank has been considered by the Air Materiel Command at Wright Field in their design of fuel tank installations,¹ by the Germans in their recommendations for improved weapons for use against aircraft,² and by the Ordnance Department in design of incendiary ammunition.³

The formation and ignition of liquid sprays from experimental tanks has been studied by the British.^{4, 5, 6, 7, 8} Unfortunately this work, so excellently begun, does not appear to have been continued to yield the delays before spray emergence as a function of mass, striking velocity, type of tank and the degree to which it is filled. A study to determine the effect of these variables on the liquid spray has been initiated at Aberdeen and recently at the University of Denver by contract from the Ordnance Department. Suitable pictures are obtained by use of sunlight, but equipment permitting use of an indoor range has not yet been available for this test.

To obtain the pictures of the liquid spray, a series of ultra-high speed motion pictures (about 4000 frames per second) were made of the bullet impact into a water-filled self-sealing fuel tank. The camera was placed perpendicular to and approximately twenty feet to one side of the line of fire at a point even with the face of the fuel cell. Two mirrors, one above and one below the line of fire, were used to reflect sunlight onto the impact surface of the tank and to illuminate a two foot distance in front of the tank. A black background was used. The camera and lighting arrangement is shown in Figure 29.

It had earlier become apparent, from a series of microflash pictures taken in preliminary tests, that not all self-sealing fuel tanks were suitable for use as targets in liquid spray studies. Those tanks with relatively thick outer layers of celastic or other non-rubber material included for structural strength were not suitable for spray tests with the present photographic technique. This latter type of tank construction is fairly typical of so-called rigid, non-metallic tanks. The so-called collapsible tanks usually have 2 layers of rayon fabric on the outside. These however, are usually quite thin compared to the outer layers of the rigid tank.

¹TSEPP-144-1698, "Summary of Data on Fires and Explosions in Aircraft Fuel Tanks," 13 Sept 1946.

²Ministry of Supply, Reports and Translations No. 835, 1 May 1947, "New Methods for the Improvement of Anti-Aircraft Efficiency," by Voss.

³Record of Army Ordnance Research and Development, Volume 2, Book 2, "Small Arms Ammunition," Office of the Chief of Ordnance, Research and Development Service, January 1946, page 57.

⁴AC 7290, SIMR E144, Jan 1945, "Penetration of Fuel Tanks by Projectiles. I. Formation and Ignition of Liquid Sprays," by H. C. Grimshaw.

⁵AC 7863, SIMR E145, Feb 1945, II. "Formation of Liquid Sprays, Snapshot Photography," by W. C. F. Shepherd and V. O. Hardy.

⁶AC 7865, SIMR E146, Feb 1945, III. "Formation of Liquid Sprays From Experimental Tanks," by W. C. F. Shepherd and V. O. Hardy.

⁷SIMR E153, June 1945, IV. "Characteristics of the Sprays Produced by 0.303 In. Bullets in Stable Flight," by W. C. F. Shepherd and V. O. Hardy.

⁸SIMR E155, June 1945, V. "Liquid Motion Set Up by 0.303 In. Bullets Fired Downwards into Fuel Tanks," by W. C. F. Shepherd and V. O. Hardy.



FIG. 29. Ultra-High Speed Camera Set-up for Photographing the After Effects of Bullet Entry into Fuel Cells. Mirrors are used to reflect sunlight onto the face of the fuel cells.

The Goodrich B-25 bomb bay tank is a rigid type tank with a thick outer ply of fabric. The results of firing into an empty Goodrich tank with Cal. 0.50 ball ammunition are illustrated in Figure 30. The pictures were taken at 4000 frames per second. The first two strips show the bullet impact and the succeeding 11 frames. Evidently a spray of tank material appears in less than 1/4 millisecond after impact. Strip 3 shows the appearance of this spray 12 and 13 milliseconds after impact. Strip 4 shows the spray after 40 milliseconds. The maximum spray appears in this strip. Clearly, this type of tank is unsuitable for a study of liquid spray without major modification of technique.

Figure 31 shows the results of a similar impact on an empty U.S. Rubber B-25 bomb bay tank. This tank has a relatively thin outer fabric layer. The pictures show that this tank would be suitable for liquid spray studies, since a limited amount of spray appears from the tank wall.

Strips 1 and 2 of Figure 32 show the results of impact by Cal. 0.50 ball ammunition on an empty replica Heinkel tank made in this country. This tank does not have a thick outer ply of fabric and there appears very little spray from the tank wall. Strip 1 shows the impact and strip 2 is a typical of all the succeeding frames.

Strips 3 and 4 of Figure 32 and the strips in Figure 33 depict the results of firing into a water-filled Heinkel replica tank. The liquid spray first appears as shown by the arrow in strip 4 of Figure 32. This was at the 29th frame or about 7 milliseconds after impact. The development of this spray is shown in the strips of Figure 33. In strip 2 of Figure 33 a second spray is evident. This spray comes from the tank filler cap which ruptured as a result of impact. The maximum development of the visible spray in Figure 33 is about two feet.

It is expected that the results of the series of fuel tank spray tests with bullets and fragments of various masses and striking velocities will be of great value when coupled with fragment flash results and the incendiary bullet functioning tests described earlier. Also, whereas the photographic observations of incendiary bullet functioning may be a valuable technique for evaluating production lots of incendiary ammunition, the photographic observations of fuel tank behavior upon bullet impact may greatly assist the evaluation of fuel tanks presented for acceptance testing.

EFFECT OF HIGH EXPLOSIVES ON FUEL TANKS

Firings of bare TNT charges both within and on the outside of gasoline filled fuel tanks have been nearly completed. For bare TNT charges it appears that as much as one pound of TNT placed at the geometrical center of a gasoline-filled B-17 feeder tank will completely demolish the tank but will not result in fire. The lowest weight of charge used was 1/16 pound TNT. This charge also caused leakage but no fire. A one pound charge of black powder was also detonated within a B-17 fuel cell, on the theory that the slower burning black powder should result in temperatures above the ignition temperature at the outside of the tank where a proper vapor-air mixture for ignition would be found. However, this charge likewise resulted in leakage without ignition.

Tests have been conducted to determine the effect of static firing of bare TNT charges placed within B-17 wings but at 12 different distances from fully loaded gasoline fuel cells. The weights of charges used at these respective positions were separately increased at each position until a fire assessed as causing

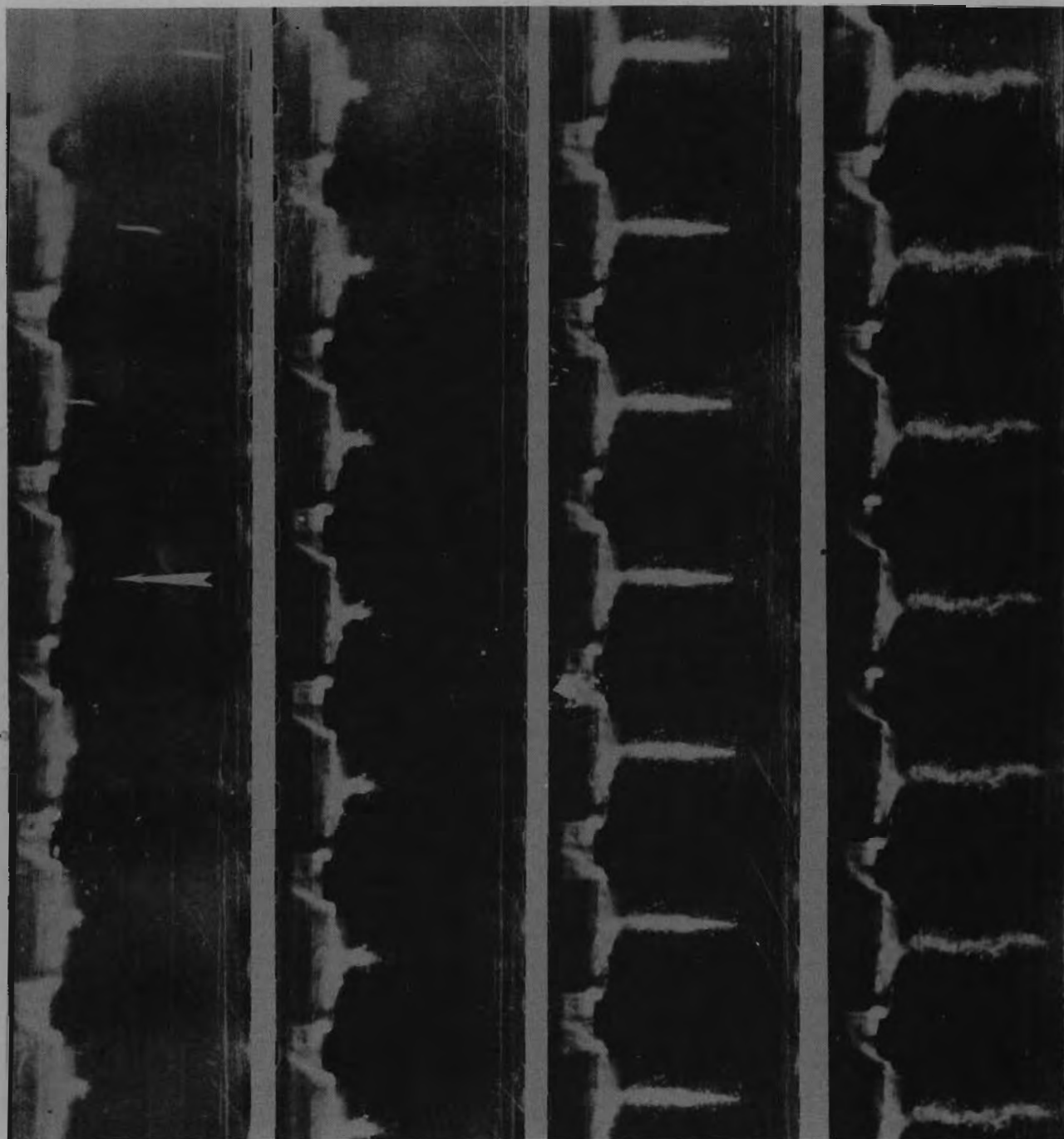


FIG. 30. Bullet Entry into Empty Goodrich Bomb Bay Cell. Strips 1,2: Point of impact through 3 milliseconds. Strip 3: Beginning at 12 milliseconds. Strip 4: Beginning at 40 milliseconds. Arrow denoted emergence of spray of tank fabric. Ammunition used: Cal. .50, Ball, at 175 yards.

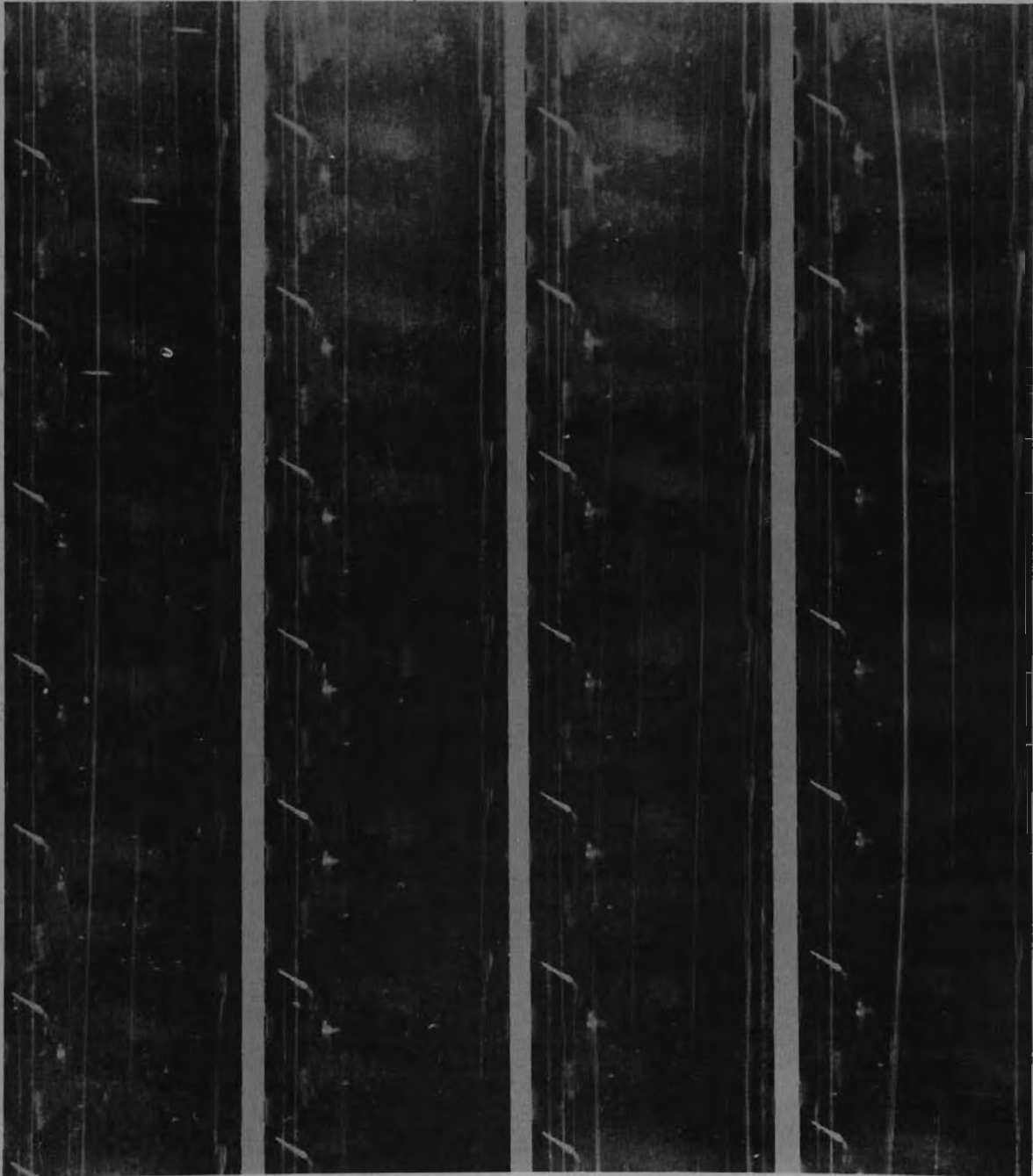


FIG. 31. Bullet Entry into Empty US Rubber Bomb Bay Cell. Strip 1: Shows point of Impact. Strip 2: Begins at 2 milliseconds. Strip 3: Begins at 6 milliseconds. Strip 4: Begins at 17 milliseconds.



FIG. 32. Bullet Entry into a Heinkel Cell. Strip 1: Impact into empty cell and first millisecond. Strip 2: Begins milliseconds. Strip 3: Impact into full cell. Strip 4: Begins 6 milliseconds after impact into full cell. Arrow denotes emergence of spray from impact hole. Ammunition used: Cal. .50, Ball, at 175 yards.

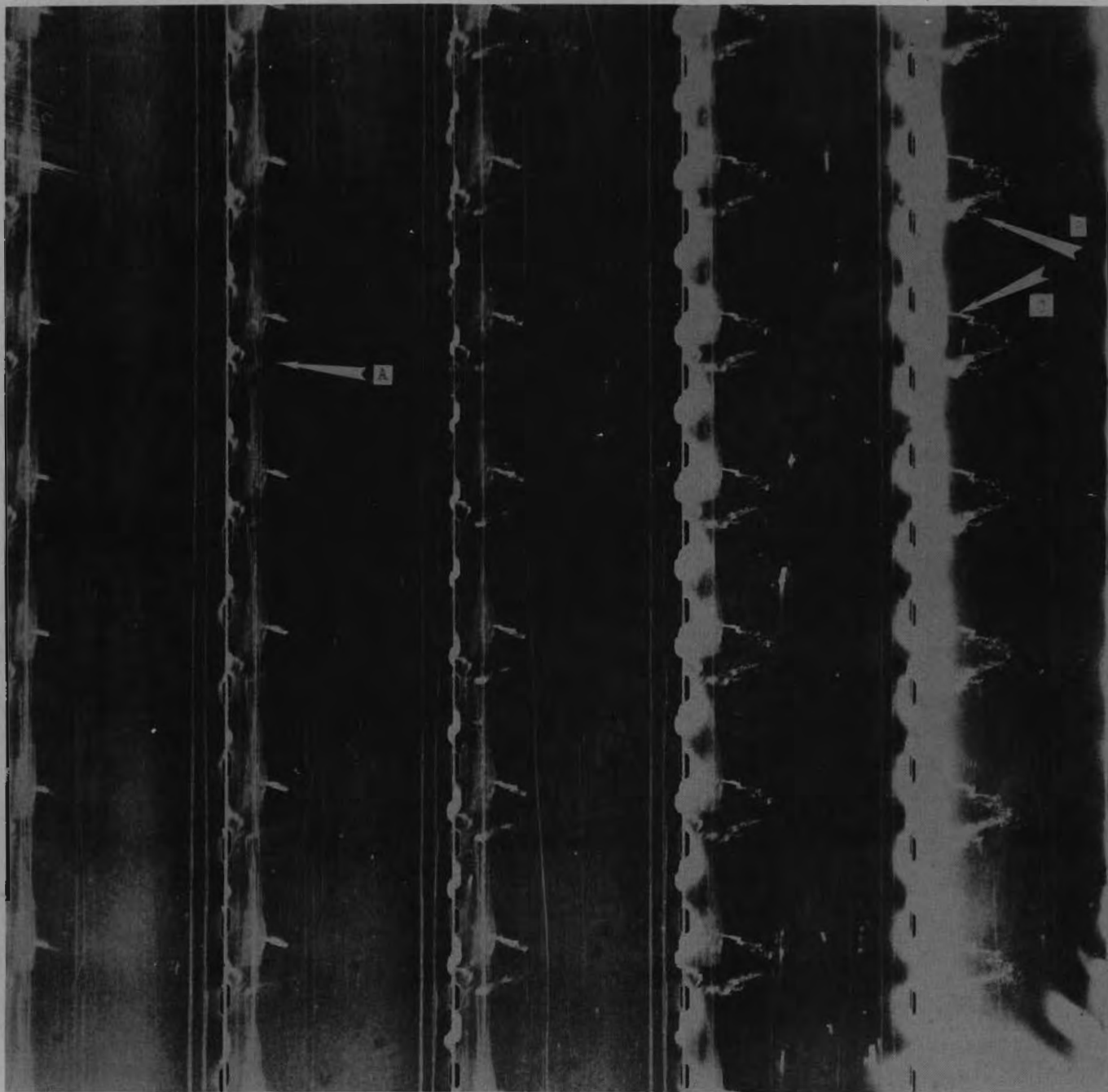


FIG. 33. Bullet Entry into Heinkel Cell. Strip 1: 12 milliseconds after impact into full cell. Strip 2: Begins at 24 milliseconds. Strip 5: Begins at 29 milliseconds. Arrow "A" denotes emergence of spray from filler cap. Arrow "B" shows later spray from filler cap. Arrow "C" denotes spray from point of impact.

100A damage resulted. In no case, however, was the weight of charge allowed to exceed the weight sufficient for a kill due to structural damage. At eight positions out of the twelve, approximately half the weight of charge required for "A" structural damage was sufficient for an "A" kill due to fuel cell fire. In the other 4 cases, no fires resulted from charges smaller than those required for structural kills. Tests with bare charges in a number of different positions on the outside of the wing skin are now in progress. These positions simulate those obtained with superquick fuze action on an HE shell.

STATIC DETONATION OF 20MM HEI, M97

In order to study the ability of a small caliber high-explosive incendiary shell to ignite a fuel cell, the 20mm HEI, M97 was statically detonated in various positions on the outside in the wall, and on the inside of gasoline-filled fuel cells. The shell was statically detonated since the M75 fuze gives erratic functioning and the position of functioning is important to fuel tank ignition. The results for this shell when fired at various ranges are presented in an earlier part of this report.

The results of the static detonations are shown in Figure 34. It is evident that the shell will ignite a gasoline-filled cell through but a small part of its path, namely where part of the shell is in the tank wall. The shell detonated in some positions outside the cell wall did not even result in leakage. Those inside the cell and adjacent to its wall caused leakage but no fire. One shell detonated in the center of a B-17 main tank did not cause any penetration of the tank wall. It is important to remember that kerosene-filled tanks will generally be more difficult to ignite than those filled with gasoline.

It is evident that proper fuzing is vital for a small caliber HEI shell. A fuze which shows promise of being developed to function in the wall of a fuel tank is the German hydrodynamic fuze, AZ-9501, which has been the subject of a careful study.¹

EFFECT OF HOLLOW CHARGES ON AIRCRAFT FUEL TANKS

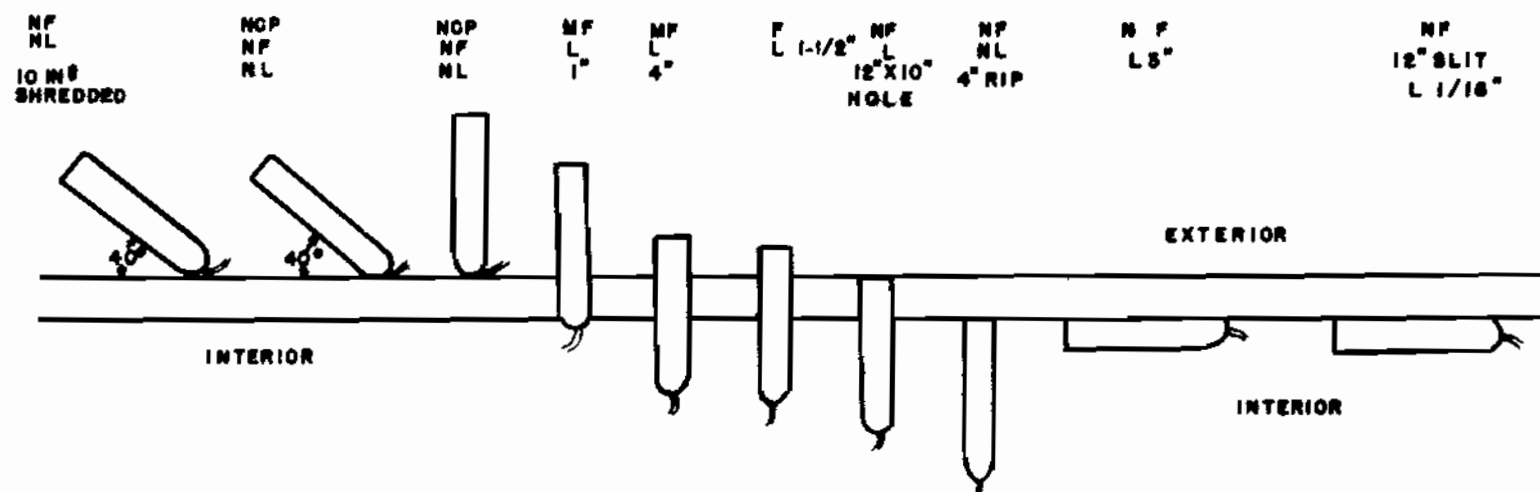
Hollow charges of various sizes are being fired against B-17 wings with gasoline-loaded fuel cells and also against bare fuel cells. The object of the tests is to determine the effect of weight of explosive, type of liner and stand-off distance against various types of fuel tanks. Detailed analysis of results awaits the completion of the firings. An outline of results to date follows:

The U.S. Navy Cavity Charge Mk II was filled with 305 grains of 50/50 cast pentolite, with a 25 grain tetryl booster, drilled for Engineer's Special Blasting Cap. The charges were placed in contact with the exterior surface of the top and bottom skins and directed towards gasoline-loaded cells. Fifteen of the Mk II charges have been thus detonated at various positions on the B-17 wing. Of these fifteen, three resulted in small fires fed by leaking fuel, three in flash fires which extinguished themselves, 4 in non-self-sealing leaks and 5 in self-sealing leaks. This one inch diameter charge is of possible use as a daughter pellet from a missile warhead and will not be tested at long stand-off from wing skin.

¹BRLM 479 (c) "Experimental Study and Appraisal of the German Hydrodynamic Fuze AZ-9501," by L. Zernow and J. M. Regan.

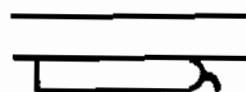
EFFECT OF 20MM HEI STATIC DETONATION AGAINST FUEL CELLS FROM TOP VIEW

B25 FUEL CELLS - FULL 220 GALLONS 100 OCTANE GASOLINE



B25 HALF FULL, SHELL ABOVE FUEL LEVEL

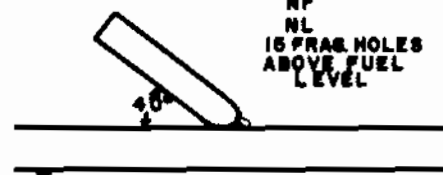
NF 1/2" SLIT, ABOVE FUEL



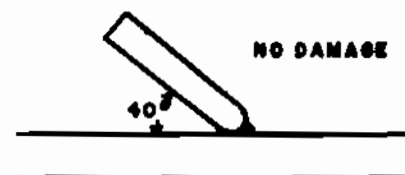
3" GASOLINE

B17 FULL

NF NL 16 FRAG HOLES ABOVE FUEL LEVEL



NO DAMAGE



CODE: F = FIRE, NF = NO FIRE
MF = MEDIUM FIRE

INTERIOR

L = LEAKAGE
NL = NO LEAKAGE

OP = CELL PENETRATED
NOP = CELL NOT PENETRATED

FIG. 34

Proposals have been made for the inclusion of hollow charges in a small caliber projectile to fire back through the base after the projectile has penetrated into the fuel tank. The Mk II charge was detonated on the inside of the gasoline-filled fuel cells at stand-off distances from the tank wall of from 0" to 2". In each of four trials, large leakage resulted. However, the fuel was not ignited in any instance so that no improvement over the performance of bare TNT charges is evident with hollow charges of this size.

The U.S. Navy Cavity charge Mk I (.74 lbs of 50/50 Pentolite, 2-1/4" diameter) was also detonated within gasoline-filled fuel cells. These charges, at stand-off distances of 0" to 3" each resulted in large fires and complete destruction of the tank. Firings within tanks with intermediate charge diameters are planned.

The Mk I charge was also detonated at respective stand-off distances of 10 feet and 19 feet from bare gasoline-filled cells with large fire resulting at the closer distance and large non-self-sealing leakage resulting at both distances.

The U.S. Navy Cavity Charge Mk III (1.4 lbs 50/50 Pentolite, 3" diameter) was detonated 16 times against bare gasoline-filled self-sealing fuel tanks at stand-off distances of from 10 feet to 100 feet. Large fires were always obtained at distances up through 30 feet, and mixed results in the region from 35 feet through 60 feet. The detonation at 100 feet stand-off resulted in non-self-sealing leakage but no ignition. This same charge was detonated against gasoline-filled self-sealing fuel tanks with a sheet of .102" 24ST Dural placed 1 ft. in front of the tank and perpendicular to the line of fire. At distances of 60 ft., 75 ft., and 100 ft., there were obtained one, one and three large fires respectively out of the same number of charges detonated. At 150 feet, 2 small fires out of 5 charges were obtained and at 200 ft., the one round fired to date resulted in slight seepage of fuel, but no fire. Further firings with this charge are in process to determine the sensitivity curve for ignition. It is interesting to note that fires have been obtained at distances where the jet spray has diverged to about 2 feet in diameter.

Five rounds were also fired with the rocket warhead, M6A3 (bazooka, .5 lb. Pentolite, 2" diameter). Large fires were obtained up to 8 feet stand-off and no fires beyond that distance.

Firings are also contemplated with long stand-off distances for 15 and 40 lb. hollow charge warheads.

FUEL HOSE

In general, the fuel hose on the target aircraft has been easily ignited, especially when under pressure. This hose was of the self-sealing type but may have been especially vulnerable because of aging. It is understood that non-self-sealing hose is presently planned for new aircraft. A recommendation to this effect was made as a result of recent tests at Wright Field.¹ Arrangements have been completed for the procurement of sufficient lengths of new hose for tests at Aberdeen, of both self-sealing and non-self-sealing types.

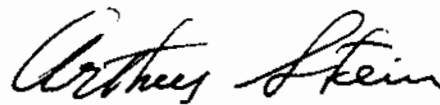
¹ MCREXP-524-1829, Power Plant Laboratory, "Evaluation of Resistance of Aircraft Hose to High Caliber Gunfire," 24 February 1948.

STRATOSPHERE CHAMBER

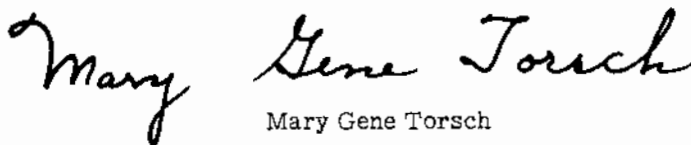
Tests are planned to study ignition at high altitudes in a stratosphere chamber, available at Aberdeen, within which it is planned to conduct the tests at pressures down to about 1/10 of an atmosphere and temperature down to -55°C . In this chamber it will be possible to study fragment flash at high altitudes and the ignition of spray under laboratory conditions. The feasibility of conducting actual gunfire tests against gasoline filled tanks in the chamber is still under study.

ACKNOWLEDGMENT

This report was written under the general direction of Mr. H. K. Weiss. The firings were conducted by proof directors assigned to the Terminal Ballistics Branch of the Arms and Ammunition Division, Development and Proof Services. Assessments of damage were made by Air Force and Navy officers assigned to the Optimum Caliber Program. Mr. M. M. Lavin, Mr. C. J. Thomas, and Major R. I. Schnittke of CHORE assisted in the preparation of the fuel tank data on a working visit to the Ballistic Research Laboratories. The authors are indebted to Mr. Ed S. Smith for his constructive review.



Arthur Stein



Mary Gene Torsch

APPENDIX A

THE MECHANISM OF FUEL TANK IGNITION BY INCENDIARIES*

The purpose of this section is to discuss the general problem of fuel tank ignition and to apply the data to the airborne aircraft. The term, "fuel tank ignition," includes both explosions and fires. Explosions occur if the ratio of fuel vapor to air is within certain limits, described later. Fires occur if that ratio is higher, up to a certain value.

The rounds discussed in the earlier parts of this report, pierced the fuel tanks both above and below the liquid surface of gasoline at an ambient temperature range of 32.9°F to 75.2°F. (Average monthly temperature of 53.83°F). In the case of kerosene, only full fuel tanks were used. The firings were made against the target on the ground. A simulated slip stream of approximately 80 miles per hour was produced by another aircraft. The damage was assessed as though the airplane were airborne. The results are recorded in Figures 2 to 25 in the first part of this report.

For the purpose of discussion this section is divided into two headings: I. Explosions and II. Fires.

I. Explosions. For an explosion to occur within a container, the concentration of fuel vapor and oxygen must lie within a definite range. A considerable amount of work has been done in this field with 100 octane (gasoline) AN-F-48A and JP-1 (kerosene) AN-F-32 fuels. The results have been summarized in Hq. AMC Wright-Patterson AFB Memo Report.¹

In this section JP-2 (kerosene) AN-F-34 has been excluded since this fuel has been replaced by JP-3 (kerosene) AN-F-58 with characteristics somewhat similar to 100 octane gasoline. As yet no study has been made of vapor pressure versus temperature or of explosive mixtures with this fuel.

In Figure 35, a plot is given of the temperatures versus total pressure (altitude), for the two types of fuels, JP-1 kerosene and 100 octane gasoline, (dotted curves). The data were taken from AMC Memo Report.² These curves are envelopes of a large number of similar curves representing different samplings. Within each of the two envelopes was superimposed a curve of temperature versus pressure (solid curves). The data for JP-1 kerosene were taken from the AMC Memo Report.² The data for 100 octane gasoline were taken from Hq. AMC Wright-Patterson AFB Memo Report.³

¹Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

²Hq AMC, Wright-Patterson AFB Memo Report Serial No. TSEAM-M5204, "Inflammability Range of J. P. Fuels Nos. PPF 45-6, PPF 45-7, PPF 45-26," 26 Aug 1946.

³Hq AMC, Wright-Patterson AFB Memo Report Serial No. Eng. 57-531-203, "Inflammability Range of Various Aircraft Engine Fuels," 21 May 1943.

*The evaluation of the vulnerability of fuel installations in different types of aircraft which have not been used in firing tests and with types of ammunition still in design stage requires an understanding of the mechanics of fuel tank ignition. This is especially true if the effects of altitude and temperature are to be properly included. A preliminary survey of the literature has been made by Dr. A. Christy, of Project CHORE, during a working visit to the Ballistic Research Laboratories and by C. F. L. Mohr, Major, USAF, assigned to the Optimum Caliber project. The results of this survey with joint comments by Dr. Christy and Major Mohr are presented.

The explosive mixtures for JP-1 kerosene (Figure 35) and for 100 octane gasoline (Figure 37) were obtained from unpublished vapor pressure curves of Materials Laboratory, Chemical Branch, Wright-Patterson AFB. At 14.7 pounds per sq. in. pressure, the composition of the explosive mixture for JP-1 kerosene is roughly between 2% (A) and 0.4% (B) by volume. The corresponding composition for 100 octane gasoline is 7% (C) and 2% (D) by volume.

It should be stressed that these curves of explosive mixtures were obtained in the laboratory under fixed and controlled conditions with a spark of a definite duration initiating the explosion. However, when incendiaries are used to initiate the explosion it was shown¹ that explosion occurs with considerably leaner mixtures than those indicated in the curves of Figure 35. Using Cal. 0.50 incendiaries with JP-1 kerosene vapor and air mixtures, explosions occur at sea level at temperatures as low as -20°F, whereas the curves of Figure 35 show that no explosions should occur at sea level below 96°F. The discrepancy of the lower limit for 100 octane gasoline is not as great.

In order to assess whether or not explosions may occur under combat conditions, the temperatures and total pressures of the fuels within the fuel tanks must be known. Tests were performed at Blythe Army Air Field² to determine the lag between ambient and fuel temperatures for several types of airborne aircraft. Two of these curves are reproduced here, Figure 36 for ascending B-24E aircraft and Figure 37 for P-38G. On these figures, altitude scales have been superimposed on the ambient temperature scales. Temperatures for various altitudes were obtained from the U. S. Department of Commerce Weather Bureau data.³ For the closest approximation to Blythe Field the data for Phoenix, Arizona were taken.

In Figure 36 for the B-24E bomber, the ambient temperature dropped during climbing (approximately 32,000 ft) from 102°F to -25°F while the fuel temperature dropped from 110°F to 92°F. In Figure 37, for the P-38G interceptor, the ambient temperature dropped during climbing (approximately 32,000 ft.) in the first 29 minutes from 107°F to 14°F, while the fuel temperature dropped for the same period of time from 104° to 100°F. For the next forty-one minutes, while the aircraft was descending, the temperature rose from 14°F to 107°F. The fuel temperature continued to drop to 90°F. Both of these curves show the enormous temperature lags that may be encountered under flight conditions.

For the above case, there was no explosive mixture, as defined in Figure 35, within the gasoline tank, as far as the temperature effect of the mixture was concerned. Figure 35 shows the temperature of the explosive mixture range to be considerably above the fuel temperatures encountered. However, as it will be pointed out later, explosive mixtures were undoubtedly present in fuel tanks when the P-38 landed, due to the lag of equilibrium pressure within the tank. If kerosene were used as the fuel, explosive mixtures would have been encountered during the flight if the ground temperature were considerably below 0°F.

The results of the simulated flight patterns quoted,⁴ show the effect of the non-equilibrium con-

¹Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

²Hq AMC, Wright-Patterson AFB Memo Report Serial No. Eng. 57-525-149, "Desert Tests of the Power Plant Laboratory at the Blythe Army Air Field, Blythe, California," 18 Aug 1943

³U. S. Department Commerce Weather Bureau, Technical Note on Upper Air Maximum Temperatures at Standard Levels over U. S. and Alaska, Revision 1943.

⁴Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

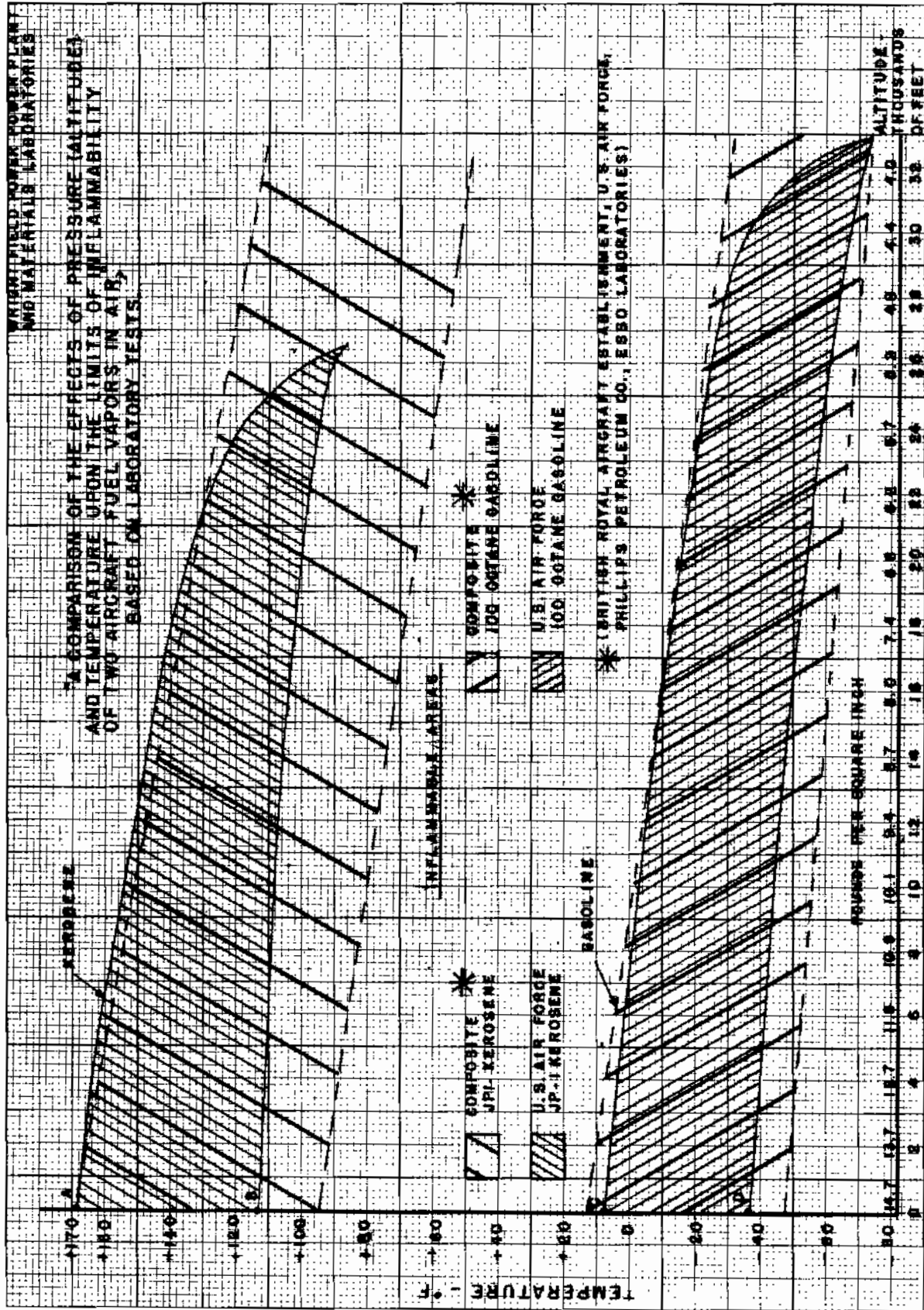


FIG. 35

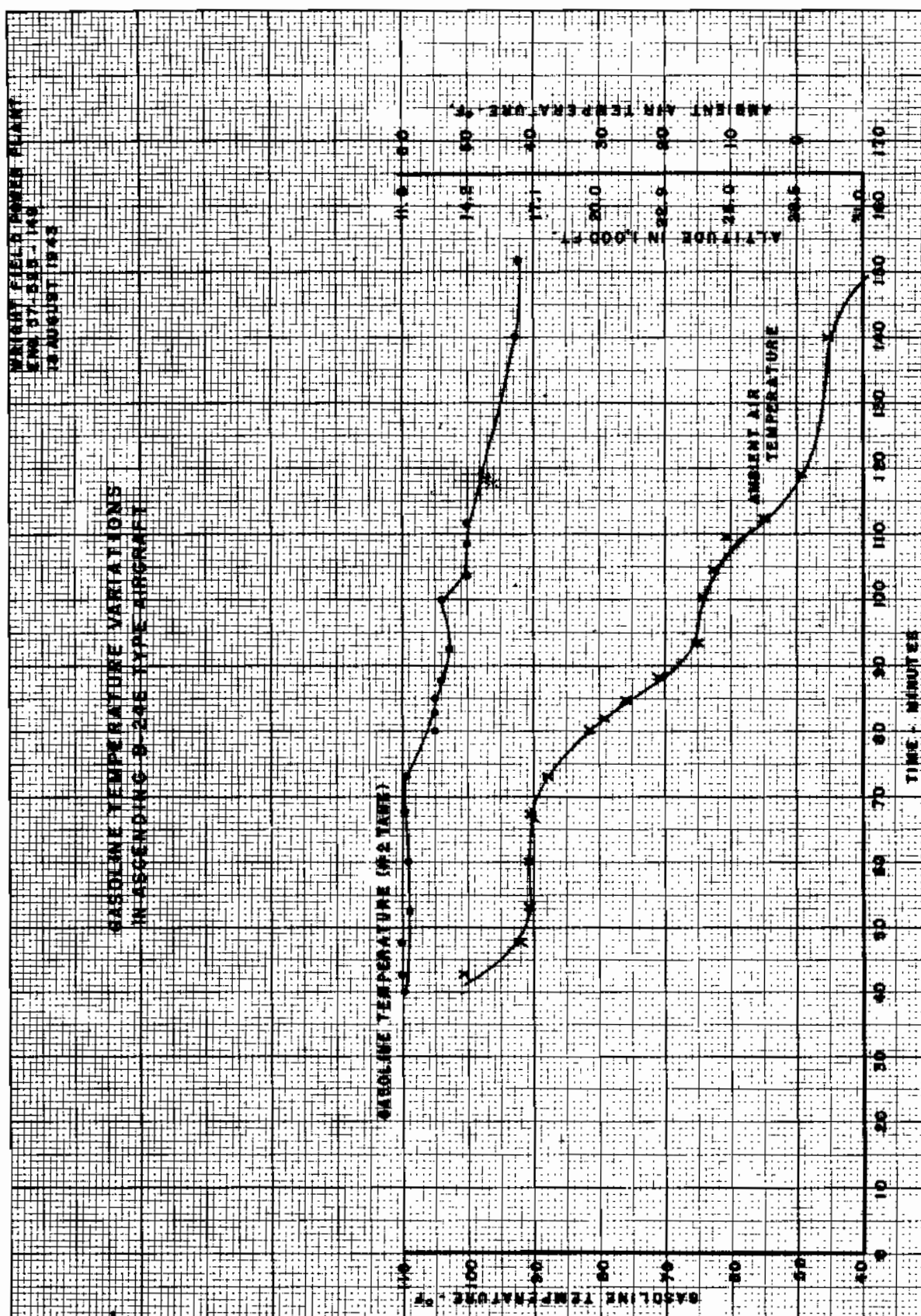


FIG. 36

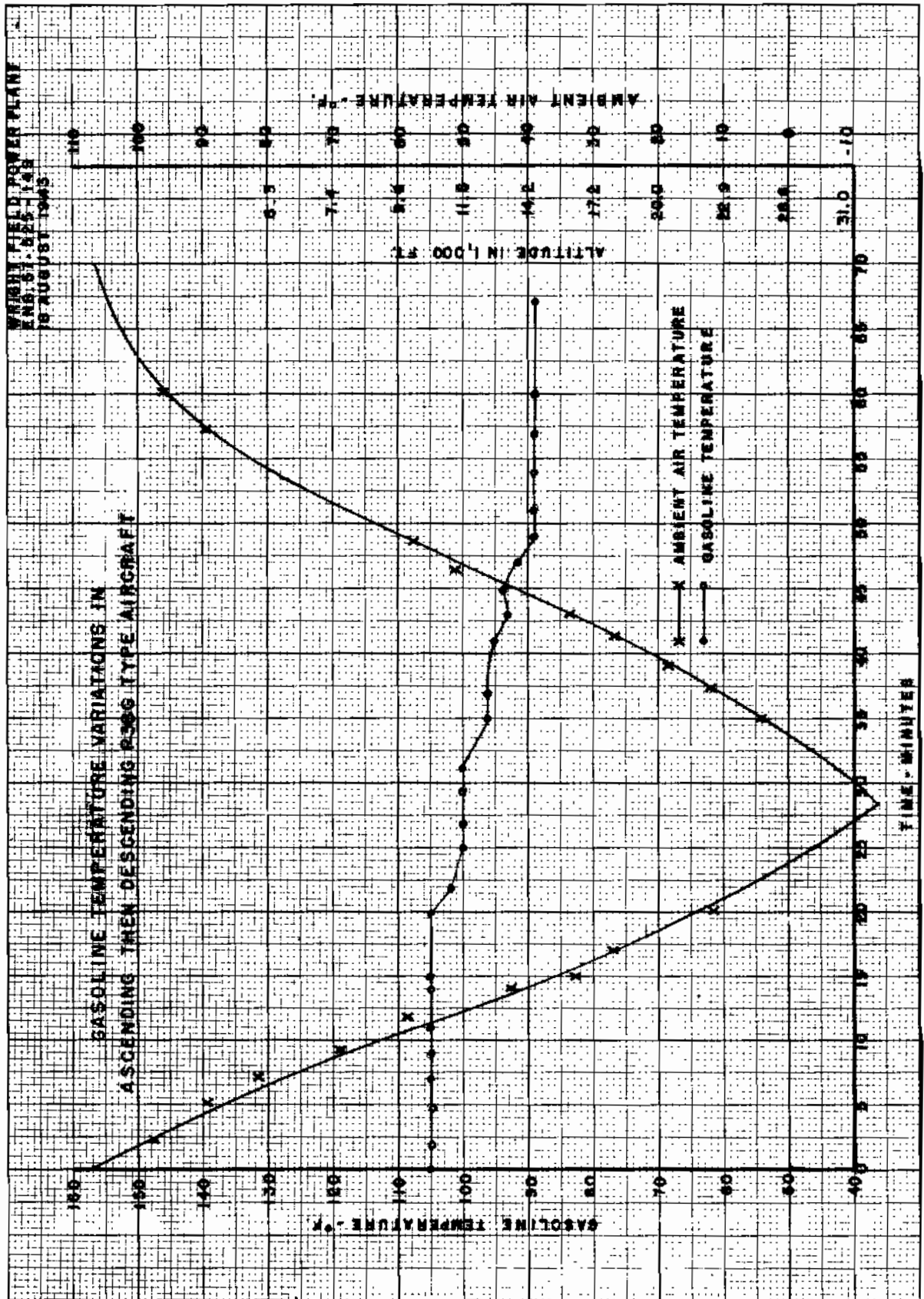


FIG. 37

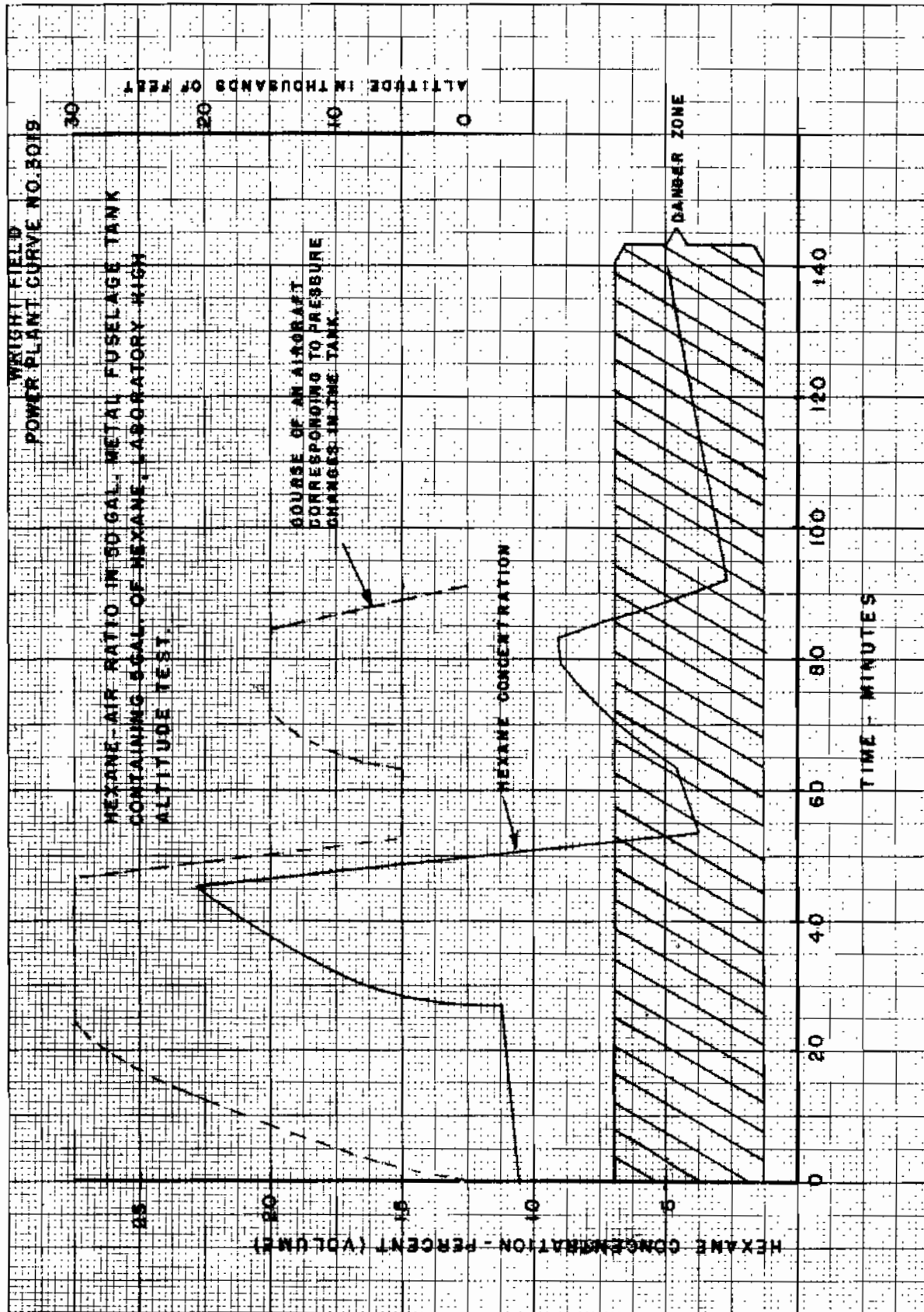


FIG. 38

ditions within the tank during flight. The tank used was a 50 gallon metal fuselage tank of a Spitfire aircraft. Figure 38 is taken from reference (3). In this flight, hexane was used as a fuel for experimental purposes. However, gasoline would have shown very similar results. This figure shows that when the aircraft descended from 30,000 feet to the ground, an explosive mixture of hexane and air remained in the tank for over 80 minutes after landing. On climbing, air and hexane vapors are removed from the tank through the vent. This increases the hexane-to-air ratio and results in a mixture too rich for an explosion. On descending, air enters the tank through the vent. Conversely this decreases the hexane-to-air ratio and results in an explosive mixture. The curve shows that, possibly due to the small size of the vent, equilibrium conditions are not reached even after 80 minutes.

In summary, factors relating to the probability of an explosion besides the experimental laboratory data are:

1. Results of incendiary firings.
2. Temperature lags encountered in actual flight.
3. Non-equilibrium conditions encountered in actual flight.

Each of these three factors indicates that the explosive limits of JP-1 kerosene and 100 octane gasoline are considerably larger than those obtained from the laboratory data.

The probability of a structural kill is a function of the size of the tank and the amount of vapor present. An explosion need not cause a structural kill directly but may cause fires or even a pilot kill, due to gasoline seepage or any of numerous other factors.

Considerable research has been conducted on the problem of purging fuel tanks, i.e., replacing air with non-combustible gases.^{1, 2} From the above discussions it appears that purging will be especially necessary if kerosene is used and it would be very desirable with gasoline. It should be noted that, since the beginning of World War II, purging was used by the Russians. The climatic conditions encountered by them made it necessary.

II. Fires. As discussed above, a richer fuel vapor-air mixture is required for fires than for explosions. No experimental data are as yet available for the upper limit of the fuel vapor to air ratio which may be applicable to an airborne aircraft.

If an incendiary round enters the tank above the liquid level and functions in an inflammable mixture the vapor will burn and either of two things will happen:

1. If the opening caused by the round is small, a low-order explosion may occur by the expansion of the resulting gases. The fire may extinguish itself due to lack of oxygen and no serious damage to the structure will result.
2. If the opening is large enough, air can enter to support combustion and a fire may result which may cause a kill.

If a round enters below the liquid level, fire may result in several ways. Due to the complexity of structure in an aircraft, fires may result in numerous ways either from a direct hit of the fuel tank by

¹Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

²U. S. Department of Interior, Bureau of Mines R13871, "Extinction of Gasoline Flames by Inert Gases," April 1946.

incendiaries or by subsequent rounds igniting the fuel which may have leaked out due to a previous hit. Fires may be caused either directly from the burning incendiary material or indirectly by metal particles which have been heated by the incendiary material.

It has been shown that, with a self-sealing rubber aircraft fuel tank, it may require about 7 milliseconds for the spray to come out after the round pierces the tank; therefore, the duration of the incendiary flash, after the round pierces the tank, must be greater than 7 milliseconds. There are other conditions, however, that have to be met before a fire occurs. The incendiary is actuated after it pierces the metal skin of the airplane. Values are given in other parts of this report of the duration, length of flash and distance of the heart of the fire from the metal plate which causes the incendiary to function. Hence, in order for fire to occur due to a direct hit by an incendiary, there must be space between the actuating skin and the rubber tank.

It is obvious that, if the self-sealing tank were adjacent to the metal skin, there would be small probability of fire caused by any one round entering the skin at zero obliquity.

On the other hand, the probability of the tank not sealing for this particular case would be greater, since, due to the petalling effect, the edges of the metal skin may prevent the tank from being self-sealing. Thus for this case, the probability of fire caused by a subsequent round in that neighborhood will increase. One may expect that, for any one type and caliber of incendiary projectile, at zero obliquity, the probability of fire may be maximum at some particular spacing between metal skin and tank. It is questionable, however, whether this spacing will be the same at other obliquities. The complexity of the effects is such that it is questionable whether much will be gained if an attempt is made to separate the effect of direct and compound hits.

It has been observed that a fire, whose source is exposed to the slip stream, is extinguished if the speed of the aircraft exceeds 110 miles per hour.¹ In the tests which have been conducted, smoke was observed while the slave ship was producing a slip stream against the target. Flames were evident only after the engines of the slave ship were stopped. It seems that an effective kill can only be produced by fires whose source is protected from the air currents of the slip stream.

As was earlier noted, the ratio of fuel vapor to air is smaller for an explosive mixture than for an inflammable mixture. Also, one may expect that, as the altitude is increased, the ratio of probability of fire to explosion will increase. At very high altitudes, however, both of these probabilities may be very small due to lack of enough oxygen to support either fire or explosion. Tests conducted by the Ordnance Department have indicated no significant difference in ignition of Heinkel replica tanks between sea level and 20,000 feet.^{2, 3}

¹ Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

² First Report on Altitude Tests of Cartridge, Incendiary, Caliber .50, M1 and Cartridge, Armor Piercing - Incendiary, Caliber .50, M8, OP No. 5374, December 1943 (C).

³ Second Report on Altitude Tests of Cartridge, Incendiary, Caliber .50, M1, and Cartridge, Armor Piercing - Incendiary, Caliber .50, M8, OP No. 5374, Project 2664, May 1944 (C).

Tests will be initiated in the very near future with a closed chamber and a stratosphere chamber to determine such probabilities. At the projected high altitudes which are contemplated for future aircraft, this effect of altitude will be extremely important, for it may well be that the probabilities are so small as to make this mode of attack impracticable.

Let

$$P = p_A + p_F, \text{ where}$$

P = total pressure,

p_A = pressure of air, and

p_F = fuel vapor pressure, a function of temperature.

Also $\frac{p_F}{p_A}$ is proportional to the fuel to air ratio discussed above and is an inverse function of P . Therefore, at some low total pressure P and corresponding high altitude, the fuel-to-air ratio will be too large for either explosions or fires. Unfortunately, no laboratory data are available on the dependence of the above ratio on temperature and total pressure. Hence, no calculations can be made to determine the minimum altitude above which no fires or explosions will occur.

APPENDIX B

FUEL TANK SURVIVAL PROBABILITY FOR "n" HITS

The figures presented in this report enable one to compute the probability that an aircraft sustaining "n" hits will survive fuel tank damage. A formula for the total probability of a kill due to fuel tank fire in "n" hits on any aircraft, including both single-shot and compound fires was developed in a previous report.¹ The development is used here because of its direct connection with the purpose of this report.

The formula (on Page 4 of this report) for the single-shot probability of an "A" kill due to fuel tank fire may be used for each of the separate fuel tank locations on the plane. The product of the single-shot survival probabilities for each fuel tank location will then be the single-shot survival probability for all the areas combined. This may be denoted by $1 - P_{A_F ss}^{(1)}$. The probability of an "A" kill due to single-shot fuel damage in "n" hits is then

$$P_{A_F ss}^{(n)} = 1 - (1 - P_{A_F ss}^{(1)})^n$$

There is an additional source of fuel tank fire damage due to the additional probability that a round may cause a fire when a previous round impacting in the same general area has caused leakage. This is a form of non-commutative compound damage as distinguished from the commutative compound damage one attains with doubly vulnerable components such as engines or pilots on a multi-engined bomber. This type of fuel tank damage is especially important when there is more than one burst on the target. Let P_{F_c} be the compound probability of a fire for a functioning penetration on a leaking cell. P_{F_c} , which would be written as $(P_{F_c}/fcn, CP)$ in the formula on Page 4 may be estimated for gasoline or kerosene from Figures 10 and 11, respectively. $P_{F_{ss}}$ is the single-shot probability of a fire for a functioning penetration of an undamaged cell. $P_{F_{ss}}$ would be written as $(P_{F_{ss}}/fcn, CP)$ in the formula for P_{A_F} and its value may be estimated for gasoline or kerosene from Figures 8 and 9, respectively.

Let $P_{F_{\Delta c}} = P_{F_c} - P_{F_{ss}}$ be the additional probability of a fire due to previous leakage and $P_{L_{ss}}$ be the probability of leakage and no fire for a single-shot hit on the target cell. $P_{L_{ss}}$ may be estimated from Table I. Then

$$P_{F_m} = 1 + \frac{P_{F_{\Delta c}} (1 - P_{L_{ss}})^m - P_{L_{ss}} (1 - P_{F_{\Delta c}})^m}{P_{L_{ss}} - P_{F_{\Delta c}}}$$

is the probability of getting at least one fire due to compounding of damage if the cell is hit "m" times. The

¹BRLM 437 "Optimum Caliber Program" by A. Stein.

probability of getting "m" hits on the cell out of "n" rounds can be calculated separately for each fuel tank area. Thus, for the near main cell (denoted by NM), this probability is

$$\frac{e^{-np_{NM}} (np_{NM})^m}{m!},$$

using the Poisson approximation to the binomial.

Then for any one fuel tank location, say for the near main cell, the probability of fire, due to compounding, for "n" hits on the plane is

$$P_{CF}^{(n)} = \sum_{m=0}^n \frac{e^{-np_{NM}} (np_{NM})^m}{m!} P_{F_m}$$

If (P_{A/F_c}) is the probability of an "A" kill on the plane due to compound fire (See Table I, parts C and D), then

$$P_{A_{F_c}}^{(n)}(NM) = (P_{A/F_c}) P_{CF}^{(n)}$$

is the probability that "n" hits on the plane will result in an "A" kill due to the additional probability of compound fires in the near main cell.

For example, if the far main cell is the only other cell containing fuel when the plane is over the target, then

$$P_{A_F}^{(n)} = 1 - (1 - P_{A_{F_{ss}}}^{(n)}) (1 - P_{A_{F_c}}^{(n)}(NM)) (1 - P_{A_{F_c}}^{(n)}(FM))$$

is the total probability of an "A" kill due to fuel tank fires in "n" hits on the plane, including both single-shot and compound fires.

An indication of the effect of compound fuel damage may be obtained from calculations made for the B-25 target in a previous report.¹ It appears from these calculations that the effect of compound damage is appreciable only where the single-shot probability is itself extremely small. From a consideration of data accumulated to date, therefore, there would seem to be but little difference in overall aircraft vulnerability for widely varying time intervals between impacts. If this is so, then from the terminal ballistic standpoint, the vulnerability of the target under repeated passes would be little different from that for one long burst with the same number of hits. The application of this fact will simplify calculations of the outcome of aircraft duels.

¹BRLM 462 "Airplane Vulnerability and Overall Armament Effectiveness", K. H. Weiss and A. Stein, pages 46-49,

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APPENDIX D

FUEL CELL FIRINGS
SUMMARIZED - 1 MAY 1948

	Gasoline Firing Record No.	Total Hits on Projected Area*		Kerosene Firing Record No.	Total Hits on Projected Area*	
		Single Shot	Com- pound		Single Shot	Com- pound
<u>B-25</u>						
<u>200 yards Rear Above</u>						
3 cm AZ	P41071	2	2			
<u>500 yards Rear and Above</u>						
Cal. .50, API-T, M20	P41050					
Cal. .50, API-T, M20	P40496	37	13			
Cal. .60, API, T39	P41051					
Cal. .60, API, T39	P40497	15	10			
Cal. .60, Inc, T36E2	P40498					
Cal. .60, Inc, T36E2	P41053	8	15			
Cal. .60, Inc, T36E2	P41054					
20mm, HEI, M97	P41055					
20mm, HEI, M97	P41056	6	3			
20mm, Inc, M96	P41070					
20mm, Inc, M96	P41073	5	16			
37mm, HE, M54	P41072	4	0			
<u>P-38</u>						
<u>54 yards Front Below</u>						
Cal. .50, API-T, M20	P42299			P42317		
Cal. .50, API-T, M20	P42302	12	14	P42314	15	14
Cal. .50, API-T, M20	P42307			P42310		
20mm, Inc, M96	P42374			P42363		
20mm, Inc, M96	P42371	18	7	P42362	16	0
20mm, Inc, M96	P42377			P42352		
<u>100 yards Rear Above</u>						
75mm, HE, M48				P41289	4	0
105mm, HE, M1				P41464	3	0
<u>200 yards Rear Above</u>						
3 cm, HE, Mk 108	P41237	10	1	P41270		
3 cm, HE, Mk 108	P41256	5	1	P41663	14	11
<u>500 yards Front Below</u>						
Cal. .50, Inc, M23	P41626			P41486		
Cal. .50, Inc, M23	P41623	12	11	P41485	10	16
Cal. .60, API, T39	P41277			P41652		
Cal. .60, API, T39	P41276	12	14	P41649	11	25
Cal. .60, API, T39	P42122					
Cal. .60, Inc, T36E2	P41632			P41656		
Cal. .60, Inc, T36E2	P41258	8	4	P41654	14	14

*Includes duds.

FUEL CELL FIRINGS (Continued)

	Gasoline Firing Record No.	Total Hits on Projected Area*		Kerosene Firing Record No.	Total Hits on Projected Area*	
		Single Shot	Com- pound		Single Shot	Com- pound
<u>500 yards Front Below (Continued)</u>						
20mm, HEI, M97	P41477	4	2	P41284		
20mm, HEI, M97				P41279	8	23
20mm, Inc, M96	P41636					
20mm, Inc, M96	P41637			P41283		
20mm, Inc, M96	P41446	18	9	P41286	12	16
<u>500 yards Rear Above</u>						
Cal. .50, API-T, M20	P41074			P41261	7	18
Cal. .50, API-T, M20	P41247	14	19			
Cal. .50, Inc, M23	P41643			P41262		
Cal. .50, Inc, M23	P41647	17	16	P41470	15	19
Cal. .60, API, T39	P41078					
Cal. .60, API, T39	P41079			P41264		
Cal. .60, API, T39	P41087	18	8	P41475	12	25
Cal. .60, API, T39	P41248					
Cal. .60, Inc, T36E2	P42378					
Cal. .60, Inc, T36E2	P41089			P41263		
Cal. .60, Inc, T36E2	P41250	15	11	P41483	13	14
20mm, HEI, M97	P41091			P41269		
20mm, HEI, M97	P41090	14	11	P41280	21	11
20mm, HEI, M97	P41253					
20mm, Inc, M96	P42383					
20mm, Inc, M96	P40499			P41268		
20mm, Inc, M96	P41255	13	16	P41281	15	18
37mm, HE, M54	P41246			P41660		
37mm, HE, M54	P41260	15	1	P41450	6	4
<u>1000 yards Front and Below</u>						
Cal. .50, Inc, M23	P41805					
Cal. .50, Inc, M23	P41803	8	18	P41793	5	31
Cal. .60, API, T39	P41810					
Cal. .60, API, T39	P42411	7	10			
Cal. .60, Inc, T36E2	P41800					
Cal. .60, Inc, T36E2	P41818	15	9			
Cal. .60, Inc, T36E2	P42425					
20mm, HEI, M97	P41791					
20mm, HEI, M97	P41827	6	11			
20mm, Inc, M96	P42400			P41822	5	11
20mm, Inc, M96	P42403	10	1			

*Includes duds.

FUEL CELL FIRINGS (Continued)

	Gasoline Firing Record No.	Total Hits on Projected Area*		Kerosene Firing Record No.	Total Hits on Projected Area*	
		Single Shot	Com- pound		Single Shot	Com- pound
<u>1000 yards Rear Above</u>						
Cal. .50, Inc, M23	P41831					
Cal. .50, Inc, M23	P41776	9	16	P41779	4	19
Cal. .60, API, T39	S44229					
Cal. .60, API, T39	P42436					
Cal. .60, API, T39	P42437	20	18			
Cal. .60, Inc, T36E2	P41782					
Cal. .60, Inc, T36E2	P42441					
Cal. .60, Inc, T36E2	P42480	12	11	P41768	6	11
20mm, HEI, M97	P41786					
20mm, HEI, M97	P41695	9	14	P41709	6	11
20mm, Inc, M96	S44231					
20mm, Inc, M96	P42482	11	3	P41702	4	5
<u>2000 yards Front and Below</u>						
Cal. .60, API, T39	P41513			P41518		
Cal. .60, API, T39	P41494			S44247	14	34
Cal. .60, API, T39	P43109	19	15	P41624		
Cal. .60, Inc, T36E2	P41677					
Cal. .60, Inc, T36E2	P42798			P41635		
Cal. .60, Inc, T36E2	P42958	9	8	P41628	11	25
Cal. .60, Inc, T36E2	P43008					
Cal. .60, Inc, T36E2	P43069					
Cal. .60, Inc, T36E2	P43086					
20mm, HEI, M97				S44253		
20mm, HEI, M97				P41615	22	12
20mm, Inc, M96	P43168					
20mm, Inc, M96	P43311					
20mm, Inc, M96	P43350	52	41	P41505		
20mm, Inc, M96	P43378			S44252	9	14
20mm, Inc, M96	P43393					
<u>2000 yards Rear Above</u>						
Cal. .60, API, T39	S44238	5	7	P41670	11	7
Cal. .60, Inc, T36E2	P41682					
Cal. .60, Inc, T36E2	P41657	7	10	P41642	8	9
20mm, HEI, M97	P41661	6	11	S44246		
20mm, HEI, M97				P41650	9	22
20mm, Inc, M96	S44237	9	5	S44239	6	6
For A-35 and P-47 Empty Firings, See BRLM 437.						
P-51						
<u>200 yards Front Below</u>						
3 cm HE, Mk 108	P41965					
3 cm HE, Mk 108	P41970	5	4			

*Includes duds.

FUEL CELL FIRINGS (Continued)

	Gasoline Firing Record No.	Total Hits on Projected Area*		Kerosene Firing Record No.	Total Hits on Projected Area*	
		Single Shot	Com- pound		Single Shot	Com- pound
<u>500 yards Front Below</u>						
Cal. .50, Inc, M23	P41842					
Cal. .50, Inc, M23	P41846	6	20			
Cal. .60, API, T39	P41863					
Cal. .60, API, T39	P41935	5	13			
Cal. .60, Inc, T36E2	P41848					
Cal. .60, Inc, T36E2	P41855					
Cal. .60, Inc, T36E2	P41857	8	5			
20mm, HEI, M97	P41957					
20mm, HEI, M97	P41960	5	7			
20mm, Inc, M96	P41946					
20mm, Inc, M96	P41949					
20mm, Inc, M96	P41955	7	23			
P-59						
<u>200 yards Rear Above</u>						
3 cm HE, Mk 108				P41669	2	3
<u>500 yards Rear Above</u>						
Cal. .60, Inc, M23				P41680	7	3
Cal. .60, API, T39				P41272	8	5
Cal. .60, Inc, T36E2				P41271	9	2
20mm, HEI, M97				P41275	5	2
20mm, Inc, M96				P41274	10	3

* Includes duds.

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ABSTRACT:

The effectiveness of incendiary ammunition against aircraft fuel systems is analyzed: The probability of obtaining a kill on an aircraft due to the vulnerability of its fuel system to incendiary projectiles is the product of the probability that a round perforates the tank, the probability that the projectile functions, the probability that the penetrating projectile ignites the fuel after functioning and perforating, the probability that the tank does not self-seal, and the probability that a resulting fire causes a kill to the aircraft. These various probabilities have been obtained as functions of striking velocity from firings of incendiary ammunition against gasoline and kerosene filled fuel tanks. Experiments under controlled conditions, designed to study the mechanics of fuel tank ignition, are described and preliminary results presented.

Fuel Tanks - Incendiary Ammunition

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