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A THEORETICAL INVESTIGATION OF A METHOD OF INCREASING THE PERFORMANCE OF ROCKET PROPELLANTS FOR USE IN TORPEDOES BY THE INJECTION OF WATER

Thesis by

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SYMBOLS

$a = \dfrac{\text{weight rate of flow of water}}{\text{weight rate of flow of propellent}}$

A = Propellent flow rate

C_F = Drag coefficient

$\overline{C}_p$ = Average specific heat at constant pressure - calories per mass of gas °K

$\overline{C}_v$ = Average specific heat at constant volume - calories per mass of gas °K

$C* = \dfrac{p_c f_t}{m}$

D = Drag of a streamlined body

D_T = Drag of a submerged body including fin drag

F = Specific thrust, pounds, per pound of propellant per second

f = fineness ratio of torpedo $\frac{L}{d}$

f_1 = friction coefficient for pipe flow

f_t = throat area of nozzle

g = acceleration of gravity - 32.2 ft. per second per second

h_f = friction pressure loss in a pipe, feet

ΔH = Enthalpy change of the gas concerned between temperatures T_1 and T_2, kilocalories per mass of gas

K = Cavitation parameter

L = Length of the torpedo

m = Mass of gas, grams

p = pressure on a submerged body

p_o = static pressure at a given submergence

p_v = vapor pressure of water at a given submergence

p_c = Chamber pressure, pounds per square inch absolute

p_e = Exhaust pressure, pounds per square inch absolute

p_f = Pressure loss in pipe due to friction, pounds per square inch

$Q_{available}$ = Heat released from the reaction, kilocalories per mass of gas formed

Q_f = Heat of formation, kilocalories per mole

R = Reynolds number

r_1 = Monopropellent system-ratio of weight of water to weight of propellent; Bi-propellent system-ratio of weight of oxidizer to weight of fuel

r_2 = Ratio of the weight of water to the weight of oxidizer

r_p = pressure ratio = p_c/p_e

$S = \frac{X}{L}$, in torpedo body equation

S = Surface area in drag calculation

T_C = Chamber temperature

T_e = Exhaust temperature

v = Torpedo volume

v_c = Chamber volume

v_e = Exhaust velocity, feet per second

v_o = Torpedo velocity

X = Distance from nose of streamlined body

Y = 1/2 diameter of circumscribing circle

$Z = \frac{Y}{d}$

$\bar{\gamma}$ = Average ratio of specific heats $\frac{\bar{c}_p}{\bar{c}_v}$

ρ = Density

$\frac{\epsilon}{D}$ = Relative roughness of a pipe

η = Propeller efficiency

SUMMARY

In this report it is shown that water injection into the rocket motor of a rocket propelled torpedo increases the range at a given speed. For a 5000 lb. torpedo having a 1750 lb. warhead, the use of a hydrogen peroxide-nitromethane-water combination yields a range about 50 percent above that which would be obtained by the use of nitromethane or of acid-aniline propellants.

Theoretically, the use of water injection increases the specific thrust, i.e., thrust per unit mass rate of flow of propellant carried. The specific thrust is increased by water injection up to 18.5 percent for nitromethane and up to 89.1 percent for liquid oxygen and octane; the specific thrust for acid and aniline, at a mixture ratio of 3, is increased up to 27.1%.

Data calculated from experimental work in connection with gas generation has shown that the increase of specific thrust for nitromethane is up to about 11.7% at L* = 868; the specific thrust measured in connection with gas generation work using acid and aniline, at a mixture ratio of 3, is increased 24.8%.

INTRODUCTION

In this paper, it will be shown that theoretically it is possible to increase the range, at a given speed, of a given torpedo or other under-water body, that is propelled by a rocket motor, by the injection and mixing of sea water with the products of combustion of the rocket fuels. By using this method of increasing the range, or speed, of a given rocket propelled torpedo, use could be made of the present day knowledge of rocket propellants, pumps, and other rocket devices. Other uses of the data presented in this paper would be in conjunction with pressurizing of vessels and for gas production in conventional missiles for turbines used for pumping.

For the purpose of this report, a rocket motor using rocket propellants with water injection for the purpose of increasing the thrust per pound of propellant, based on propellant consumption alone, is defined as a hydrojet. In this report, F is defined as the specific thrust referred to the weight of the propellant carried and all the water consumed is assumed to be pumped from the surrounding medium. F may be considered a pseudo specific impulse.

The primary use of rocket propelled torpedoes will probably be as short range, high speed underwater missiles. Due to the high rate of propellant consumption in a rocket type of motor, underwater missiles employing this type of propulsion are, of necessity, limited to relatively short ranges. For aerial torpedoes, experience in World War II has shown that for a majority of purposes, long range is not always necessary because they are usually dropped at a relatively short range. However, high speed is extremely desirable, since the high speed of the torpedo, coupled with its short running time, minimizes the effectiveness of the target's evasive maneuvers.

With present day designs, it appears that the top speed of the conventional gas-turbine-propeller driven torpedo is limited to about sixty knots by propeller cavitation. The top speed may be increased slightly by increasing the propeller diameter and lowering the rotational speed to prevent excessive cavitation of the blade, especially at the tips. However, since the horsepower needed to drive the torpedo at increased speeds increases very rapidly with speed it is necessary to maintain a high propeller rotational speed to enable the horsepower required to be delivered. Increasing rotational speed and larger propeller diameters again cause cavitation of blade tips to become an important factor. It is believed by personnel at the Taylor Model Basin in Washington, D. C., that it is possible to design and build a torpedo propeller that will operate at a torpedo speed of seventy knots, but that this propeller will operate in a partially cavitated condition. In this case, it appears as if the question reduces to one of maintaining a high enough propeller efficiency to allow a gas turbine and gear train to be designed that will transmit the large quantity of power required. Since the power output of the propeller is $P_{out} = P_{in}(\eta)$, any reduction of η due to cavitation requires a corresponding increase in P_{in} to maintain P_{out} constant.

Extreme design problems will be encountered as the horsepower output of the turbine gear train is increased. Because of this, and the simplicity of the rocket propulsive system, it appears desirable to investigate the rocket type of propulsive system. Any method that can be employed to increase the range, at a given speed, of this type of system which carries a given propellant weight, should also be carefully investigated.

On figures 17 and 19, the performance of a straight liquid propellant rocket torpedo and a hydrojet torpedo, both of 5000 pounds gross weight are compared. Assuming a 1750 pound war head for each, the straight liquid propellant torpedo has a range of 3850 yards at 50 knots, and the hydrojet torpedo using hydrogen peroxide and nitromethane as a propellant has a range of 5600 yards at the same speed. This is an increase of 45.5% in range over the straight liquid propellant rocket. At seventy knots, the liquid propellant rocket torpedo has a range of 2800 yards, the hydrojet torpedo a range of 4250 yards; an increase of 51.8%.

Problems concerned directly with high speed torpedoes are drag and cavitation. Present torpedo shapes cavitate at fairly low velocities. Once cavitation has set in, the drag increases very rapidly, and is difficult, if not impossible, to compute. To prevent a low cavitation speed, a streamlined body of the type described in the main body of the report is necessary. In this report, a streamlined body of the above type is assumed in all computations.

The chemical propellant systems computed for this report are as follows, with the maximum values of thrust per unit propellant weight flow, i.e., F given:

CHEMICAL SYSTEM	F, lb = sec/lb	PERCENTAGE OF REACTANTS		
		Oxid.	Fuel	Water
H_2O_2 - CH_3OH - H_2O	286.0 lbs. (Figure 1)	32.72	10.28	57.0
H_2O_2 - $N_2H_4 \cdot H_2O$ - H_2O	259.0 lbs. (Figure 5)	27.9	20.5	51.6
H_2O_2 - CH_3NO_2 - H_2O	301.5 lbs. (Figure 2)	17.75	21.25	61.0
LO_2 - C_8H_{18} - H_2O	405.0 lbs. (Figure 6)	24.12	6.88	69.0
$N_2H_4 \cdot HNO_3 + (CH_2)_x$ - H_2O	241.9 lbs. A solid propellant (Figure 8)	49.78	1.22	49.0
CH_3NO_2 - H_2O	256.5 lbs. (Figure 3)	53.0		47.0
RFNA-Aniline-H_2O	279.5 lbs. (Figure 9)	30.0	10.0	60.0
Ballistite - H_2O	302 lbs. A solid propellant (Figure 7)	44.0		56.0

Although the LO_2 - C_8H_{18} - H_2O system gives by far the highest value of F, it was not used in computing the sample torpedo speed range curves, since it is considered impracticable at the present time to handle liquid oxygen in aircraft torpedoes. The use of liquid oxygen would necessitate the filling of the torpedo immediately before take off, and would require a short flying time to arrive at the target with any appreciable amount of liquid oxygen left in the torpedo. The use of liquid oxygen in submarines and surface craft is also believed to be extremely hazardous and undesirable.

The chmeical systems used to compute the sample torpedo speed range curves were H_2O_2 - CH_3NO_2-H_2O and H_2O_2 - CH_3OH - H_2O. A value of

F of 301.5 pound seconds per pound was used for the H_2O_2 - CH_3NO_2 - H_2O system, at 60.0 percent water and a F of 286 lbs. at 55 percent water for the H_2O_2- CH_3OH - H_2O system, instead of higher percentages of water at approximately the same F to obtain a higher temperature for vaporization of the water and mixing of the vapor with the combustion gases. It is believed that the higher the temperature T_c, the more complete will be the vaporization and the better will be the mixing. A combustion and mixing chamber similar to that shown in Figure 20 would be necessary for this type of propulsion, with the water injected radially at the throat of the accelerating nozzle.

In this method of increasing F of a rocket propellant, only the propellants are carried in the torpedo body. The water is pumped into the torpedo from the surrounding ocean, and thus may be looked upon as more or less "free propellant". The injection of sea water into the combustion chamber decreases the exhaust velocity of the exhausted gases, but the total momentum change of the system is increased due to the greatly increased mass flow through the system. The effect of the salt in sea water on the operation of the hydrojet is not known.

While no experimental work was carried out in connection with this problem, the experimental data obtained with work on gas generation by the Aerojet Corporation and the JPL GALCIT are given in Figures 4 and Table 1. The Aerojet work was done with nitromethane plus water and the JPL GALCIT work was done with acid-aniline plus water. Since the JPL GALCIT work was done at an acid-aniline mixture ratio of approximately 3, the computations in this report on acid-aniline plus water were done at the same mixture ratio to enable a comparison to be made between the experimental work and the theoretical computations.

Two possible answers to the high speed torpedo problem may be the hydroduct or the hydropulse. However, since both of these systems will undoubtedly require many years of experimentation and development, the hydrojet type of power plant for torpedoes appears to be worthy of further study. Since all component parts have been studied and developed, the time and energy involved in developing a torpedo of this general type would be greatly reduced.

LIST OF ASSUMPTIONS

The assumptions made in this report are:

1. That the oxidation of the fuel when fuel and oxidizer are present in stoichiometer proportions is complete. This assumption was justified by calculations.
2. That only the water-gas equilibrium was considered in the calculation of systems having mixture ratios richer in fuel than stoichiometer, for temperatures below 2500°K.
3. All gas compositions were frozen upon expansion through the nozzle.
4. The torpedo is running at a depth of 25 feet.
5. That thermodynamic equilibrium is established in the reaction chambers.
6. HES 4016 Ballistite will give approximately the same performance as JPN Ballistite.
7. The hydrogen peroxide used is pure hydrogen peroxide.
8. It is not practical at the present time to use liquid oxygen operationally in torpedoes.
9. That the salt in the sea water injected will not adversely affect the operation of the motor.
10. Cooling of the rocket motor will not be a problem.
11. A streamlined shape is used for the torpedo.
12. The torpedo density is 100 pounds per cubic foot.
13. The torpedo speed is below the cavitation speed, and the bare hull drag can be computed using C_F values obtained from airship hulls.
14. The fin and interference drag is ten percent of the bare hull drag.
15. Removal of water from the stagnation point of the torpedo does not affect the pressure distribution of the streamlined body.
16. A turbo-rocket type of pump is used for propellants and water.

ASSUMPTIONS AND DESCRIPTION OF THE METHOD OF CALCULATION

The chemical systems were calculated, where possible, on the basis of stoichiemetric proportions, fuel and oxidizer. It is believed that this ratio will give the greatest energy output per pound of fuel, which is desirable in this case. For the fully oxidized systems considered, it was assumed that the only products of combustion were water, carbon dioxide, and nitrogen. Several sample calculations were made at various points to check this assumption, and while some carbon monoxide and hydrogen were formed due to the water gas equilibrium, the amounts formed were negligible, and were assumed to be entirely absent. Also, since the portion of the curve of thrust versus percent water in which we are interested in this report is in the low temperature region, it is believed that the above assumption is entirely valid. The three under-oxidized systems were computed using the water gas equilibrium at all points. All systems were assumed frozen as far as the water gas equilibrium was concerned upon expansion through the nozzle, i.e., no change in chemical composition was assumed to occur during expansion.

The calculations were made using standard thermochemical methods, using data from Refs. 1, 2 and 3.

The equations to determine the chamber temperatures are:

$$Q_{available} = \sum Q_f \text{ products} - \sum Q_f \text{ reactents} \qquad \text{(Eq. 1)}$$

$$\Delta H_{300}^{T_c} = Q_{available} = \sum \Delta H_{300}^{T_c} \text{ products} \qquad \text{(Eq. 2)}$$

The equation used to determine the exhaust velocity is:

$$v_e = \sqrt{\frac{2 \Delta H_{T_e}^{T_c}}{m}} \qquad \text{(Eq. 3)}$$

The exhaust temperature was solved for by a trial and error method which consisted of assuming an exhaust temperature, solving for T_e, using the equation $T_e = \frac{T_o}{(r_p)^{\frac{\gamma - 1}{\gamma}}}$ (Eq. 4), and correcting the assumed T_e until it agreed with the computed T_e. The exhaust pressure in all cases was assumed 25.8 pounds per square inch absolute, corresponding to a depth of torpedo run of 25 feet.

The thrust of the system per unit weight of propellant per second F, which corresponds to a pseudo specific impulse, was computed from the relation $F = v_e(1 + a)$ (Eq. 5).

The chemical systems computed were as follows, with the maximum value of F for each system given:

	SYSTEM	F		PERCENTAGE OF REACTANTS		
				Oxidizer	Fuel	Water
1)	$H_2O_2 - CH_3OH - H_2O$	286.0 lbs.		32.72	10.28	57%
2)	$H_2O_2 - N_2H_4 \cdot H_2O - H_2O$	259.0 lbs.		27.9	20.5	51.6
3)	$H_2O_2 - CH_3NO_2 - H_2O$	301.5 lbs.		17.75	21.25	61
4)	$LO_2 - C_8H_{18} - H_2O$	405.0 lbs.		24.12	6.88	69
5)	$N_2H_4 \cdot HNO_3 + (CH_2)_x - H_2O$	241.9 lbs.		49.78	1.22	49
6)	$CH_3NO_2 - H_2O$	256.5 lbs.	(Ref. 4)	53		47
7)	RFNA-Aniline - H_2O	279.5 lbs.	(Ref. 5)	30	10	60
8)	Ballistite - H_2O	302 lbs.		44		56

From the values of maximum F given, it is seen that substantial gains in fuel economy can be obtained by the use of water injection.

As shown by present rocket experience, these theoretical values will be approximately ten percent higher than the values that could actually be obtained in practice. The values of v_e, F and I_{sp} obtained from the theoretical calculations on practically all rocket propellants are about ten percent higher than the values obtained experimentally.* In the case of the hydrojet, work on gas generation has produced experimental values that are approximately eighty percent of the computed ones. For example, at a water ratio of 45.7% with acid-aniline, the effective exhaust velocity, v_{eff}, based on propellant consumption only, experimentally is 7090 feet per second. Theoretically, this value should be 8850 feet per second. Also, at a water ratio of 30%, C* for nitromethane experimentally is 3000 feet per second at L* = 868; theoretically the value of C* is 3770 feet per second. The fact that the above experimental values are only approximately eighty percent of the calculated ones is probably due to poor motor design. Motor design could undoubtedly be improved with greater experience with this type of motor, and this would bring the experimental results more nearly in agreement with the theoretical ones.

Systems 1, 2, 3, 4, and 5 were computed on the stoichiometric ratio of oxidizer to fuel. The acid-aniline-water system was computed on an acid to aniline mixture ratio of three to one by weight to allow a comparison of the theoretical values with experimental points. This comparison is shown in Table I. The theoretical nitromethane-water system is compared with the experimental values obtained by the Aerojet Engineering Corporation in Figure 4. In

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* For values of L* commonly used in present day motors.

this curve, values of C* are plotted versus percent water. The theoretical and experimental points for this curve were taken from Ref. 10.

The ballistite used in the computations was the HES 4016 ballistite. This ballistite was used instead of the more common JPN ballistite merely to simplify computations. Since the composition of these ballistites does not differ greatly, the performance of the two should be very nearly the same. The composition of these two ballistites is given in Table II.

In all systems using hydrogen peroxide, the hydrogen peroxide was assumed to be one hundred percent peroxide, i.e., it contained no water. If a peroxide containing water were used, less sea water would be injected, so that the total amount of water entering the reaction chamber would be the same.

The hydrazine nitrate system was selected to give a comparison with the ballistite system. Since hydrazine nitrate is slightly over-oxidized, a small percentage of wax (2.4% of the hydrazine nitrate by weight) is added to bring the system to the stoichiometric condition. The heat of formation of hydrazine nitrate is from Ref. 11.

As will be seen from Table III the $LO_2 - C_8H_{18} - H_2O$ system gives by far the highest value of F. This is due, in part, to the high heat of combustion of gasoline when burned completely in oxygen, thus permitting large quantities of water to be injected before a low temperature is reached in the reaction chamber. This system was not used to compute the speed range curves of a sample torpedo, since it is not believed practical at the present time to use liquid oxygen in torpedoes. The use of liquid oxygen in torpedoes would probably entail the use of liquid oxygen generators, together with storage facilities, on the ships of the Navy, and would necessitate the filling of the torpedoes immediately before firing. This would mean that aerial torpedoes would have to be filled shortly before takeoff, and that the time of flight of the plane before launching the torpedo would have to be fairly short. Many of these difficulties undoubtedly could be overcome, and then the liquid oxygen torpedo engine would be a serious competitor with other types of torpedo propulsion. Toward the end of World War II, the Japanese had developed a gaseous oxygen torpedo, the Type 93. This torpedo also used sea water as a diluent. The power plant was a 2 cylinder reciprocating engine driving propellers.

Serious objection may be raised to the use of nitromethane and concentrated hydrogen peroxide in torpedoes, but with proper handling techniques these chemicals are fairly safe and stable in storage.

Part of the data for the theoretical nitromethane curve (Figure 3) was taken from Aerojet Report R-47, Item #4 (Vol. 5), and GALCIT Project Design Charts. The data for Figure 4 was taken from Aerojet Report TRM-19. Part of the data for the acid-aniline curve was taken from an as yet unpublished JPL GALCIT report (4-27) and the GALCIT

Project Design Charts. The experimental results for the acid-aniline table were taken from JPL GALCIT report # 4-27.

In all underoxidized systems, the low temperature points were checked for carbon deposition, and the lowest chamber temperatures shown on the curves are above the point where carbon starts to deposit. Sample calculations for a fully oxidized system, an underoxidized system, minor components and for carbon deposition are shown at the end of the report. (Appendices A, B, C and D).

In this study, it is assumed that sea water is the water injected into the combustion chamber. At the present time, it is not known whether the salt present in the sea water would adversely alter the operation of the jet motor. The effect of the salt would have to be determined experimentally. In the propellant calculations, fresh water was assumed. In computing water entrance hole size, to be discussed later, a volume of sea water sufficient to get the mass of fresh water needed was used.

Since the values of maximum thrust per pound of propellant all occur at fairly low chamber temperatures, and since large quantities of water are available for cooling, the cooling of the rocket motor should not be a problem.

In computing the performance of the two sample torpedoes, data was taken from Ref. 9. This data referred to a certain streamlined shape, (Fig. 10), volume and surface area of this shape, (Figs. 11 and 12), and structural weights as a percentage of gross weight based on a study of existing torpedoes, (Fig. 13). The streamlined body used in the sample performance calculations is defined by:

$$Z^2 = 2.3390S - 9.0022S^2 + 17.82385S^3 - 17.6885S^4 + 6.5279S^5 \quad S = \frac{x}{L}, \; Z = \frac{y}{d}$$

(Fig. 10)
(Eq. 6)

The volume of a body defined thus, is given by:

$$V = \int_0^{\ell} \pi \, y^2 dx = \frac{\pi}{4} \, d^2L \int_0^1 Z^2 ds = 0.7 \frac{\pi}{4} \, d^2L$$ (Fig. 11) (Eq. 7)

The surface area of this body is given by:

$$S = \int_0^{\ell} \pi \, y dx = \pi \, dL \int_0^1 Z^2 ds = 0.8 \, \pi \, dL$$ (Fig. 12) (Eq. 8)

A torpedo of 5000 pounds gross weight was assumed, and assuming an average torpedo density of 100 pounds per cubic foot (based on a study of present day torpedoes) and a fineness ratio of 10, the diameter, length and surface area of the torpedo can be computed.

The bare hull drag on this body below the cavitation speed can be computed from the relation $D = C_F \, 1/2\rho \, V_o{}^2S$ (Eq. 9) where C_F is a function of the Reynolds number, and is given in Fig. 14. The values of C_F used in Equation 9 are from an experimentally determined curve made from test on bare airship hulls. These hulls were streamlined bodies of the same general type as that defined by Equation 6. It will be seen that this curve, labeled "airship hull" in Fig. 14 is parallel to, but slightly above, the C_F vs. R curve for a flat plate. S is the total wetted area of the bare hull. In this paper, the fin and interference drag was assumed to be ten percent of the drag of the streamlined body. By using the above streamlined shape, the drag can be computed with good accuracy, since the pressure drag is small, and needs only to be checked by experiments. With the present day torpedo shapes, this is not the case, since the pressure drag of these shapes is ten to fifteen percent of the total drag.

Since the present day torpedo shapes cavitate badly at high speeds, even with an ogive nose, it is believed that the future high speed torpedoes, no matter what the propulsive system, will have to assume a streamlined shape of the form given by an equation of the type of Equation 6. Near 70 knots and above, even these streamlined shapes will begin to cavitate at shallow depths. Once general cavitation sets in and the torpedo is traveling in a bubble, the drag is greatly increased, and erratic behavior will result due to the inability of the control surfaces to reach the water for control.

Cavitation of an underwater body will begin when the pressure over the body, or over a part of the body, equals the vapor pressure of the fluid. Using this fact, a cavitation parameter K may be defined as follows:

$$\frac{P - P_o}{1/2\rho V_o^2} = \frac{P_v - P_o}{1/2\rho V_o^2} = -K \qquad \text{(Eq. 10)}$$

For a given fluid and depth of run, $P_v - P_o$ is a constant, and the dynamic pressure $1/2\rho V_o^2$ is proportional to $1/K$. Thus, for any given body the minimum of the pressure ratio $\frac{P_v - P_o}{1/2\rho V_o^2}$ is equal numerically to the cavitation parameter K. The pressure distribution curve also shows the point on the underwater shape at which cavitation begins. From the curves of pressure distribution over a Mk 13 torpedo, it is seen that the cavitation parameter for this torpedo is 0.78 (Fig. 15). From the pressure distribution curve of the streamlined body used in this report it is seen that the cavitation parameter is 0.23 (Fig. 10).

Knowing the cavitation parameter of any body and the vapor pressure of the fluid at a given submergence the maximum speed without cavitation for any given depth of run, or the depth of run needed to prevent cavitation for any given speed, may be computed from Eq. 10.

Assuming certain weights for the motor, pumps, gas generating apparatus and war head, (See Appendix E) and determining the structural weight from Fig. 13, the weight of propellant to be carried can be obtained. Three percent of the propellant weight is assumed to be used for gas generation to drive the pumps. This assumption is probably low.

The total drag (D_T) is assumed to be ten percent greater than the bare hull drag computed by equation 3 due to the control surfaces. Dividing D_T by F gives the propellant flow rate A needed to overcome this drag. The actual flow rate through the exhaust nozzle is greater than the propellant flow rate by a factor $(D'_T/F)a$. The propellant flow rate A, divided into the propellant weight carried less three percent, gives the time of burning t_p of the rocket system. This value of t_p multiplied by the velocity in yards per second gives the range R. A sample calculation of the Range-Speed curve for the H_2O_2 - CH_3NO_2 - H_2O system is given at the end of the report. (See Appendix E).

In the sample torpedo design, the water for injection into the rocket motor was assumed to be taken from the stagnation point at the nose of the torpedo, at a velocity of 20 feet per second. This required a 1.630 inch diameter hole and pipe for the required water flow at 75 knots. The pressure drop due to friction in the pipe (smooth walled) was 6.09 psi. The frictional loss was computed from the equation $h_f = f_1 \frac{L}{D} \frac{V^2}{2g}$ (Eq. 11), where f_1 is given as a function of Reynolds number in Fig. 16, and h_f is the head loss due to friction. A smooth walled pipe was assumed of relative roughness $\frac{\epsilon}{D} = 1 \times 10^{-6}$. For a seventy-five knot torpedo this gives a total head at the water pump of 127.9 psia, which is several times the 30 to 35 pounds per square inch absolute head at the pump entrance which is considered necessary to prevent cavitation at the pump entrance of high speed centrifugal pumps. At higher speeds, the total head at the pump entrance would be increased. The total head at the pump entrance was computed by $P_T = p_0 + 1/2\rho(V_0^2 - V_1^2) - p_f$ (Eq. 12). The water entrance hole size was selected by balancing flow velocity in the pipe against friction loss in the pipe and loss of dynamic head due to the motion of the water away from the stagnation point at various torpedo velocities. The size of the water entrance hole was selected which gave a reasonable size hole, friction loss, and water velocity, and a total head at the pump intake sufficient to prevent cavitation at low operating speeds. It is believed that the amount of water taken from the stagnation point would not change the pressure distribution along the body appreciably, and thus not affect the drag. The optimum size of water entrance hole, the optimum position of this hole, and the change of drag due to the opening in the torpedo body would have to be determined exactly by experiment. In this report it is assumed that the motion of the water away from the stagnation point does not affect the pressure distribution along the body.

In computing the sample range speed curves for the assumed torpedo, an attempt has been made to assume weight values consistent with those chosen in reference 9 for the component parts. In this way a direct comparison can be drawn between the hydrojet torpedoes (Fig. 17 & 18) and the straight liquid propellant torpedo (Fig. 19). The major difference between these two types of torpedoes is that the straight liquid propellant torpedo is assumed to be gas pressurized by a gas generator, while the hydrojet torpedoes are assumed to be of the turbo-rocket type, since pumps are needed in any case to pump the water into the reaction chamber. The liquid propellant rocket torpedo of reference 9 is based on an "average" propellant of types now in use. Going to a pump system would probably not decrease the total weight of the dry torpedo, since a heavy structure is needed for strength purposes, especially in an aerial torpedo where it is launched at high speeds and from fairly high altitudes.

A table of the performance characteristics for several service and projected torpedoes from Ref. 9 is shown in Table 4 for general interest.

Just prior to the completion of this report, Ref. 8 was published by the Massachusetts Institute of Technology, which deals with the same subject matter as the first part of this report.

CONCLUSION

From the data presented in this report, it may be concluded that it is theoretically possible to increase the performance of a jet propelled torpedo by injecting water from the surrounding ocean. It is not known if the salt in the sea water would alter the operation of the rocket motor, but it is believed that any effect would be small, and would not adversely affect the operation. The effect of salt on the motor performance would have to be determined experimentally.

Since a large percentage of the jet exhaust is water vapor that should condense shortly after coming in contact with the cool sea water, a torpedo of this type should have much less wake than present day torpedoes. The noise level of the propulsive system would have to be determined by tests.

Any type of rocket propelled torpedo would probably be limited to a high speed and relatively short range due to the high specific propellant consumption of rocket units. It would seem impractical to go to this type of propulsion for low speeds and long ranges for torpedoes of the sizes used today.

The best propellant system from the point of view of thrust per pound of propellant consumed per second (F) investigated in this report is the liquid oxygen-octane system. However, it is believed impractical to use liquid oxygen at the present time due to handling difficulties. Objection may be raised to the other systems investigated due to the fact that hydrogen peroxide and nitromethane under certain conditions may become highly explosive. However, experience has shown that with proper handling techniques all of the chemicals investigated may be handled and stored safely. All of the propellants in use today have certain desirable and certain undesirable characteristics. The propellants selected for any particular use would be based on a compromise between the desirable and undesirable characteristics of a given propellant for a given application.

In computing sample torpedo speed range curves it was shown that at 70 knots the range of the hydrojet torpedo using the H_2O_2 - CH_3NO_2 - H_2O propellant system can be increased 51.8% over the range of the straight liquid propellant rocket torpedo. The range of a hydrojet torpedo using the H_2O_2 - CH_3OH - H_2O propellant system is increased 44.6% over the range of the liquid propellant rocket torpedo at 70 knots.

Since present day torpedo shapes begin to cavitate at relatively low speeds, future high speed torpedoes will probably have to assume a streamlined form. Once cavitation begins, the drag increases rapidly. The drag of these streamlined shapes can be computed quite accurately by computing the skin friction drag using values of C_F that have been experimentally determined for streamlined bodies. Even the streamlined body begins to cavitate at about 70 to 80 knots.

Since the efficiency of propellers operating under cavitated conditions decreases rapidly as cavitation increases it may be impossible to use a gas-turbine-propeller torpedo propulsion system at speeds much above 50 knots, at which speed cavitation on practically all designs has already begun. At high speeds jet propulsion may be the only kind of propulsion that can be used. The water injection type of propulsion system presented in this report is one type of jet propulsion for torpedoes that could be proven and developed, if practical, very rapidly, since all of the component parts of this system have been studied and developed to a fairly high degree. The propellants, high speed pumps, gas turbines to drive them, and the gas generating systems have all been used in other applications. The main problems in developing a water injection torpedo would be the study of the effects of the salt in the sea water on performance, the noise produced by the jet, and the fitting of the various previously developed components together into an operating torpedo.

The control of any high speed torpedo is a problem that will have to be solved no matter what propulsion system is used.

Cooling of the rocket motor and any other parts that may need to be cooled could be readily accomplished by the large quantity of water needed in the operation of the hydrojet.

Experimental results show that an increase of up to 24.8 percent in F can be obtained with acid-aniline and water, and an increase in F up to 11.7 percent can be obtained with nitromethane and water. (Figures 3 and 4), and (Table 1). Theoretical calculations show that for acid-aniline and water, F is increased up to 27.1 percent, and for nitromethane, F is increased up to 18.5 percent by use of water injection. The experimental results probably could be brought into closer agreement with the theoretical results by improved motor design.

REFERENCES

1. Bichowsky and Rossini, "Thermochemistry of Chemical Substances".

2. Hirschfelder, Curtis, McClure, and Osborne, "Thermodynamic Properties of Propellant Gases". O.S.R.D. Report No. 547.

3. Hirschfelder, Curtis, McClure, and Osborne, "Equilibrium Constants". O.S.R.D. Report # 547.

4. Aerojet Engineering Corporation Report R-47, Item #4 (Vol. 5)

5. Galcit Report 4-27 (Unpublished)

6. Galcit Project Design Charts

7. Galcit Project No. 1, Progress Report # 16.

8. (a) Progress Report T-4 - "Thermodynamic Analysis of the Propellant Characteristics of Several Chemical Propulsion System", Harold S. Mickley, Arthur S. Collins, Antonia Boissevain, Turbo Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts.

   (b) Progress Report T-5 - "Thermodynamic Analysis of the Propellant Characteristics of the Chemical Propulsion System Hydrogen hydrate - Hydrogen Peroxide", H. S. Mickley, Adin A. Nellis, Paul M. Miller, Antonia Boissevain, Turbo Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts.

9. Torpedo Power Plants, Sections I to IV, L. G. Dunn, D. E. Hudson, R. W. Sorenson.

10. Aerojet Engineering Corporation Technical Memorandum RTM-19 of February 28, 1946, page 25.

11. Altman, D., using data from reference 1. "Heat of Formation of $N_2H_4 \cdot HNO_3$".

12. Hughes, Corruccini, and Gilbert, Journal of the American Chemical Society, Vol. 61, page 2639 (1939).

13. University of Minnesota Report No. 26 of January 9, 1945.

14. "Rocket Fundamentals", O.S.R.D. Report # 3992, Page 119.

15. Hirschfelder, McClure, Curtis and Osborne, "Thermodynamic Properties of Propellant Gases". N.D.R.C. Report No. A-116. Heats of Formation of Constituents of Ballistites.

FIG 1

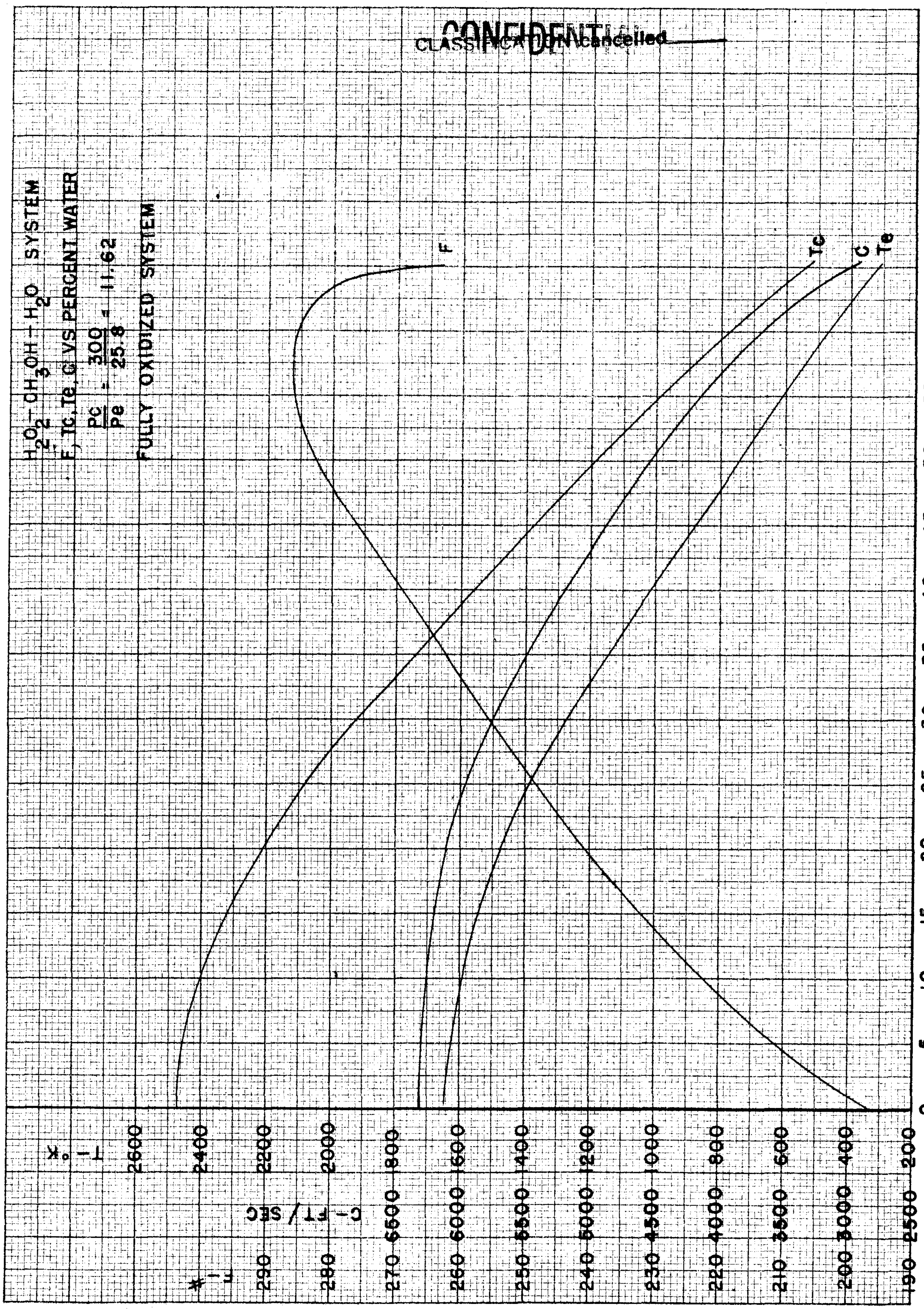
$H_2O_2 - CH_3OH - H_2O$ SYSTEM
F, Tc, Te, C VS PERCENT WATER
$\frac{Pc}{Pe} = \frac{300}{25.8} = 11.62$
FULLY OXIDIZED SYSTEM
F
Tc
C
Te
% H_2O
0
5
10
15
20
25
30
35
40
45
50
55
60
65
T - °K
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
C - FT / SEC
2500
3000
3500
4000
4500
5000
5500
6000
6500
F*
190
200
210
220
230
240
250
260
270
280
290

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FIG 2

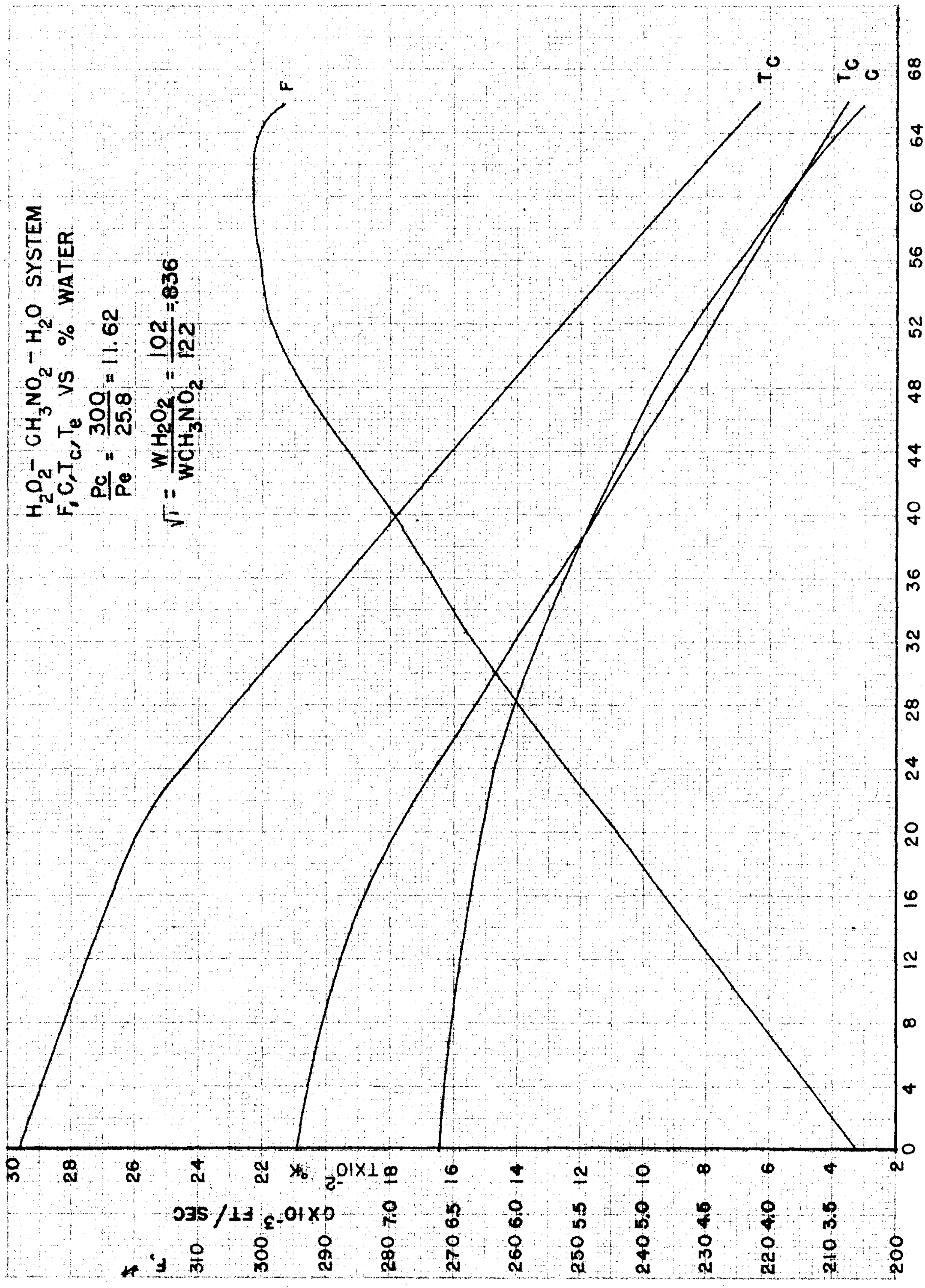

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FIG. 3

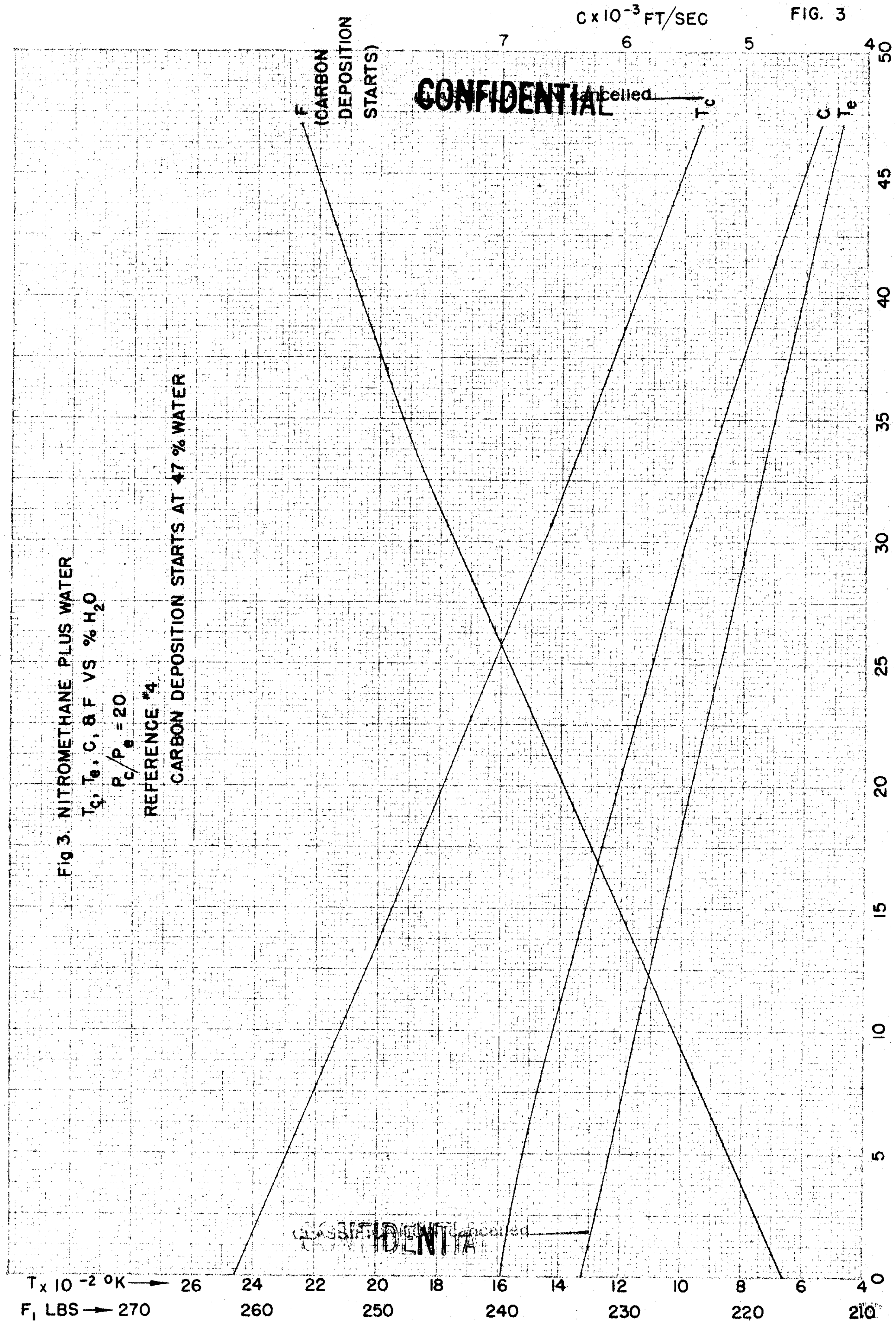
Fig 3. NITROMETHANE PLUS WATER
T_c, T_e, C, & F VS % H_2O
$P_c/P_e = 20$
REFERENCE #4
CARBON DEPOSITION STARTS AT 47 % WATER

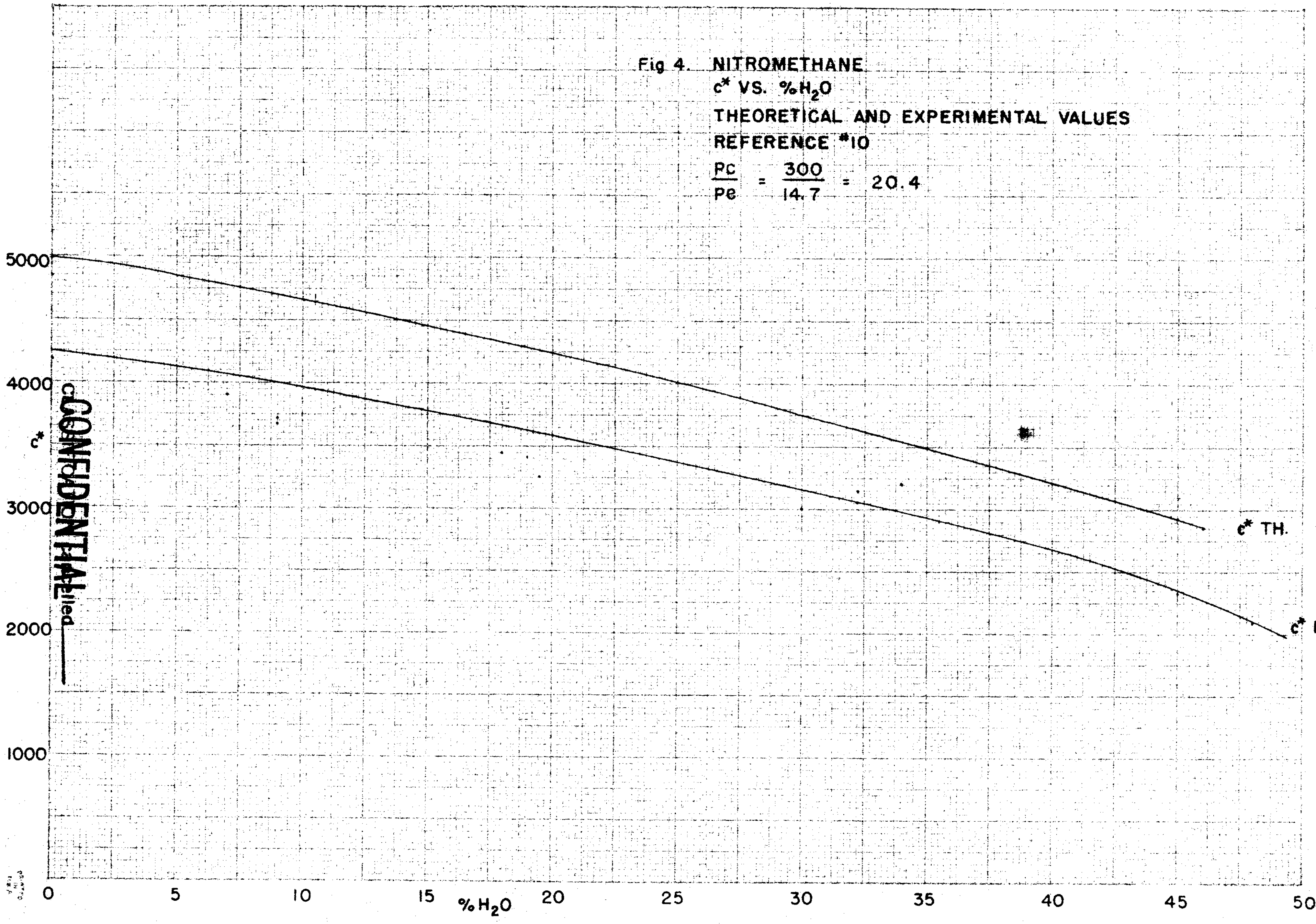

Fig 4. NITROMETHANE
c^* VS. $\% H_2O$
THEORETICAL AND EXPERIMENTAL VALUES
REFERENCE #10

$$\frac{Pc}{Pe} = \frac{300}{14.7} = 20.4$$

FIG 4

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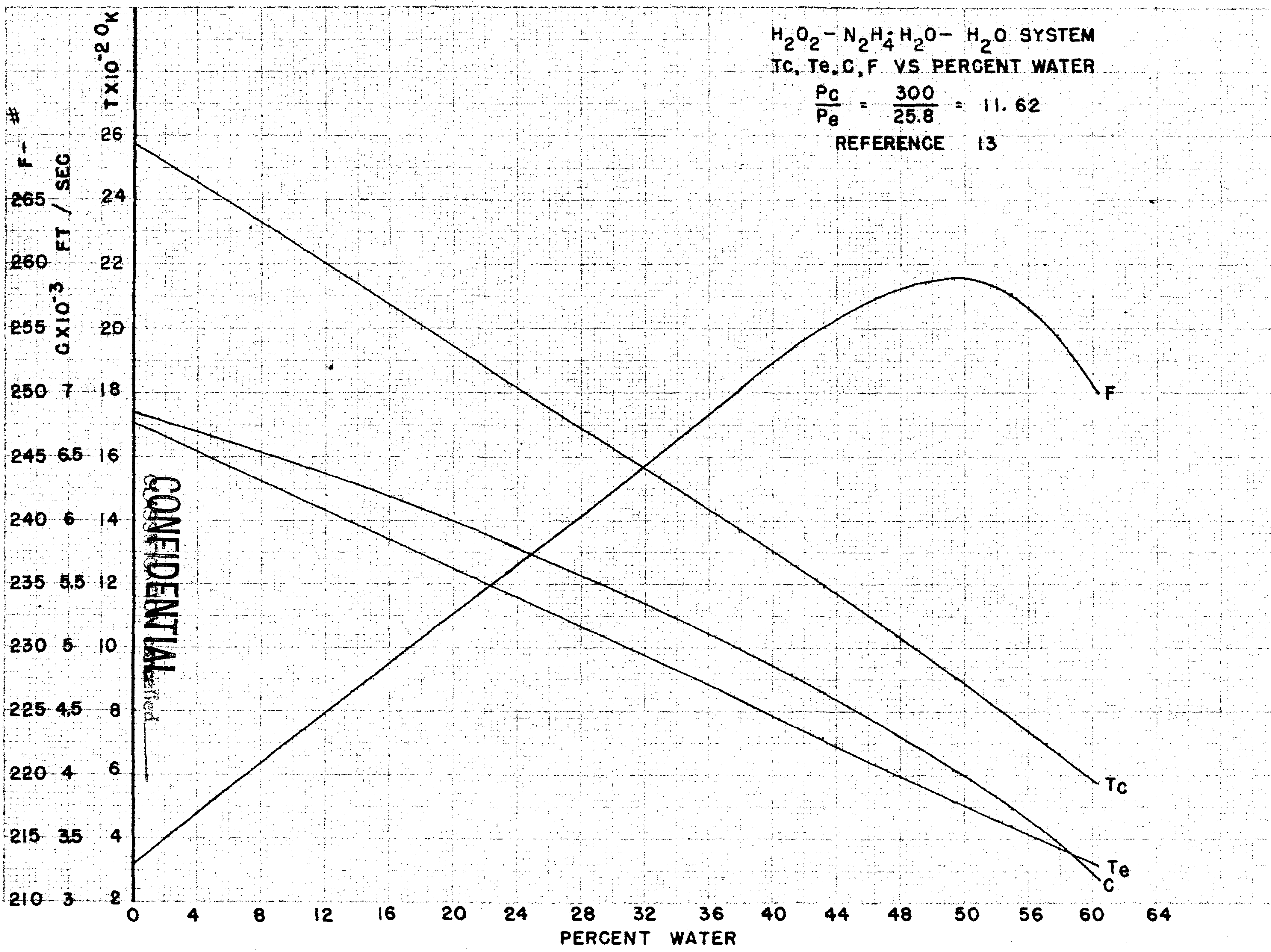

$H_2O_2 - N_2H_4{:}H_2O - H_2O$ SYSTEM
Tc, Te, C, F VS PERCENT WATER
$\frac{Pc}{Pe} = \frac{300}{25.8} = 11.62$
REFERENCE 13

FIG 5

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CLASSIFICATION cancelled

FIG 6

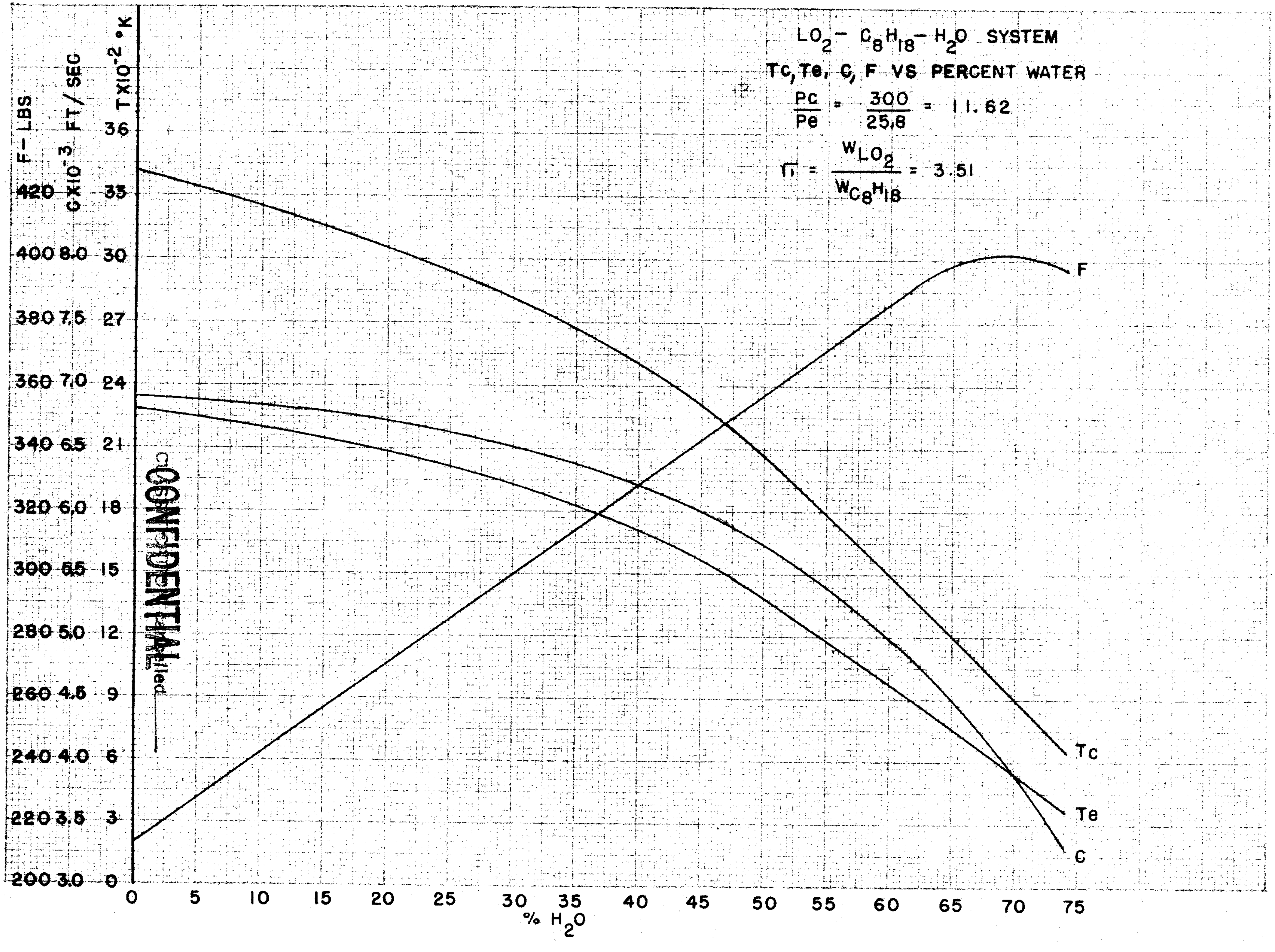
LO2 – C8H18 – H2O SYSTEM
Tc, Te, C, F VS PERCENT WATER
Pc/Pe = 300/25.8 = 11.62
r = WLO2/WC8H18 = 3.51
F – LBS
C X10^-3 FT/SEC
T X10^-2 °K
420
400 8.0 30
380 7.5 27
360 7.0 24
340 6.5 21
320 6.0 18
300 5.5 15
280 5.0 12
260 4.5 9
240 4.0 6
220 3.5 3
200 3.0 0
36
33
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
% H2O
F
Tc
Te
C

FIG. 7

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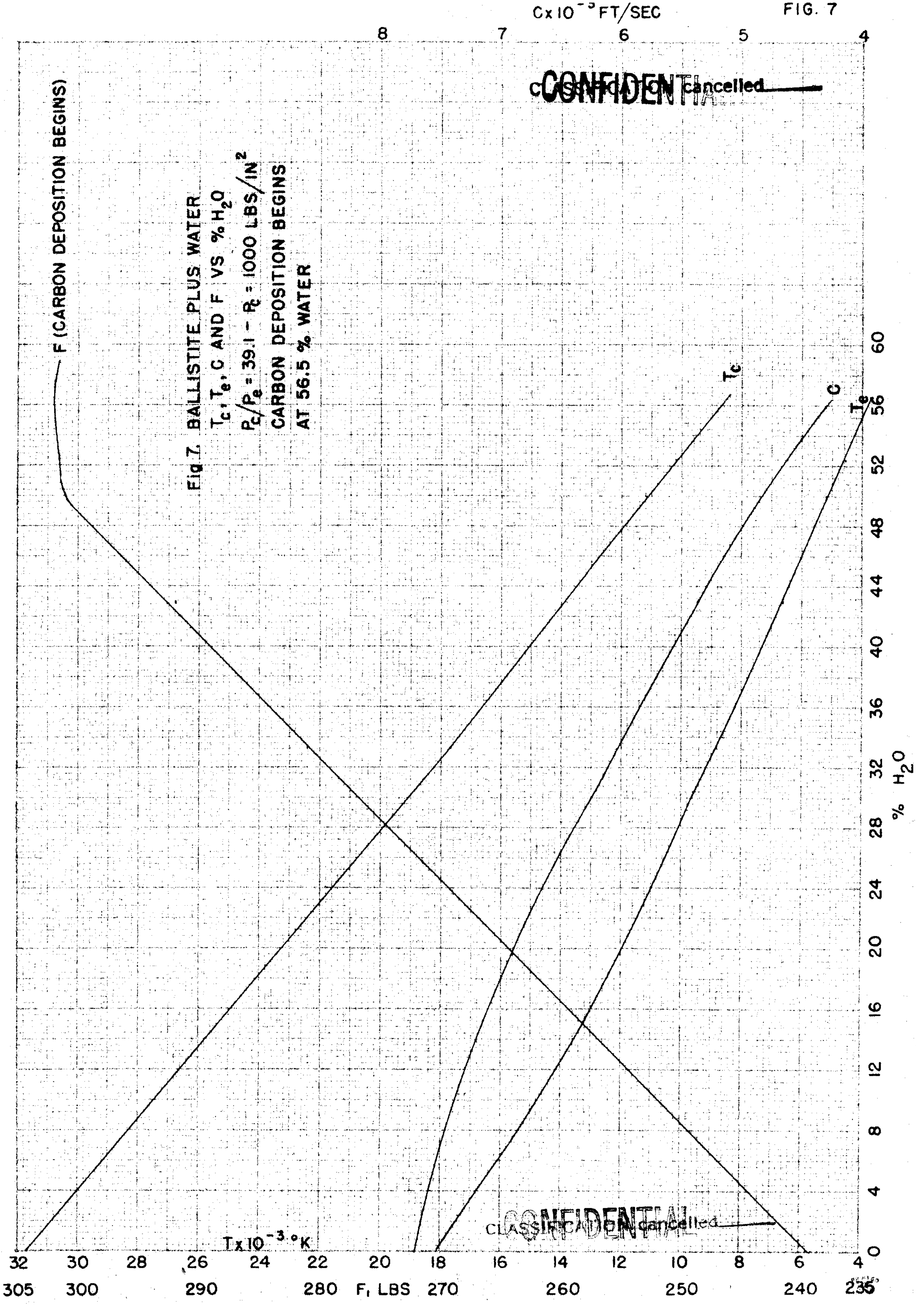
Fig 7. BALLISTITE PLUS WATER
T_c, T_e, C AND F VS % H_2O
P_c/P_e = 39.1 – P_c = 1000 LBS/IN^2
CARBON DEPOSITION BEGINS
AT 56.5 % WATER

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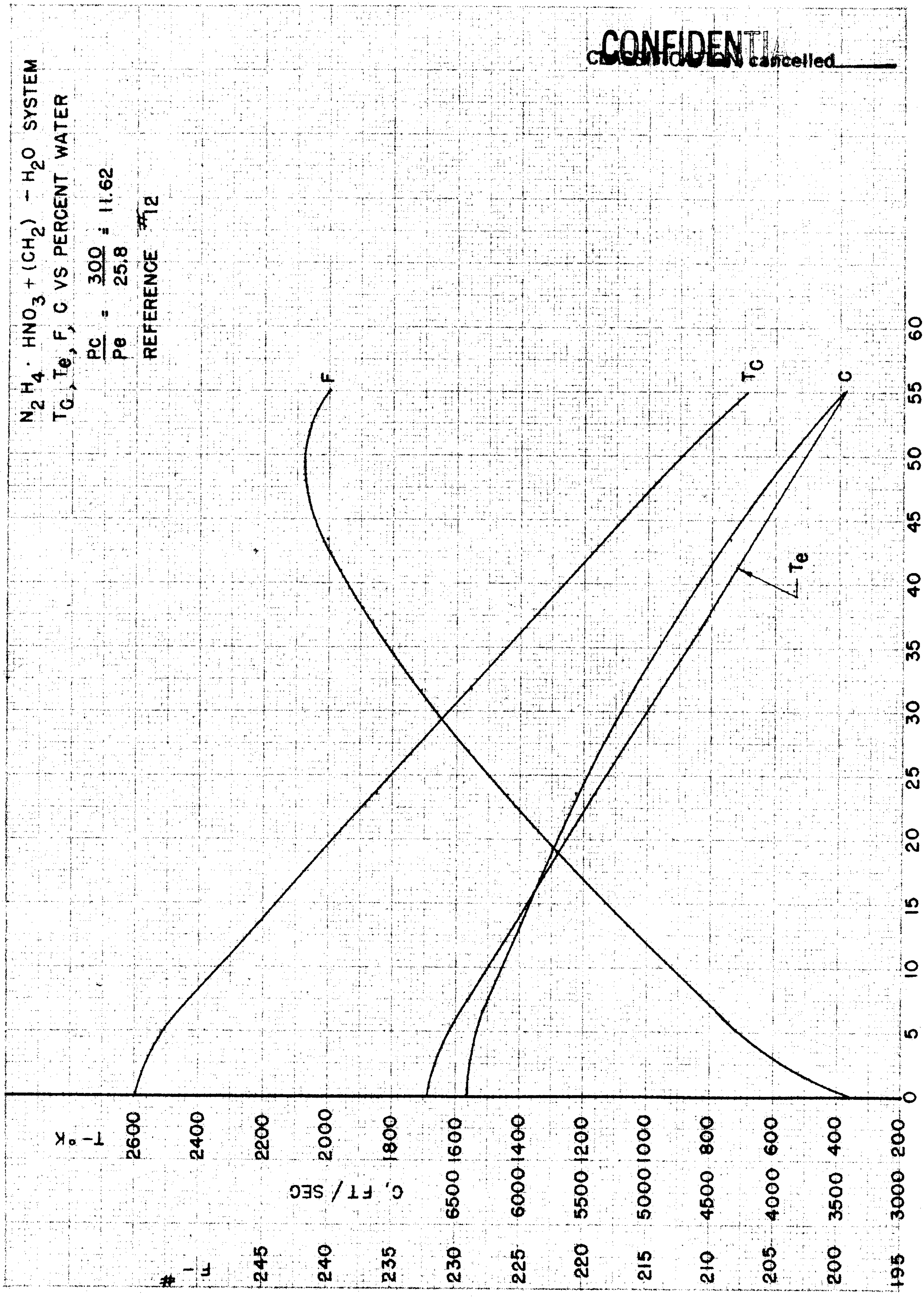


$N_2H_4 \cdot HNO_3 + (CH_2) - H_2O$ SYSTEM

T_C, T_e, F, C VS PERCENT WATER

$\frac{Pc}{Pe} = \frac{300}{25.8} = 11.62$

REFERENCE #12

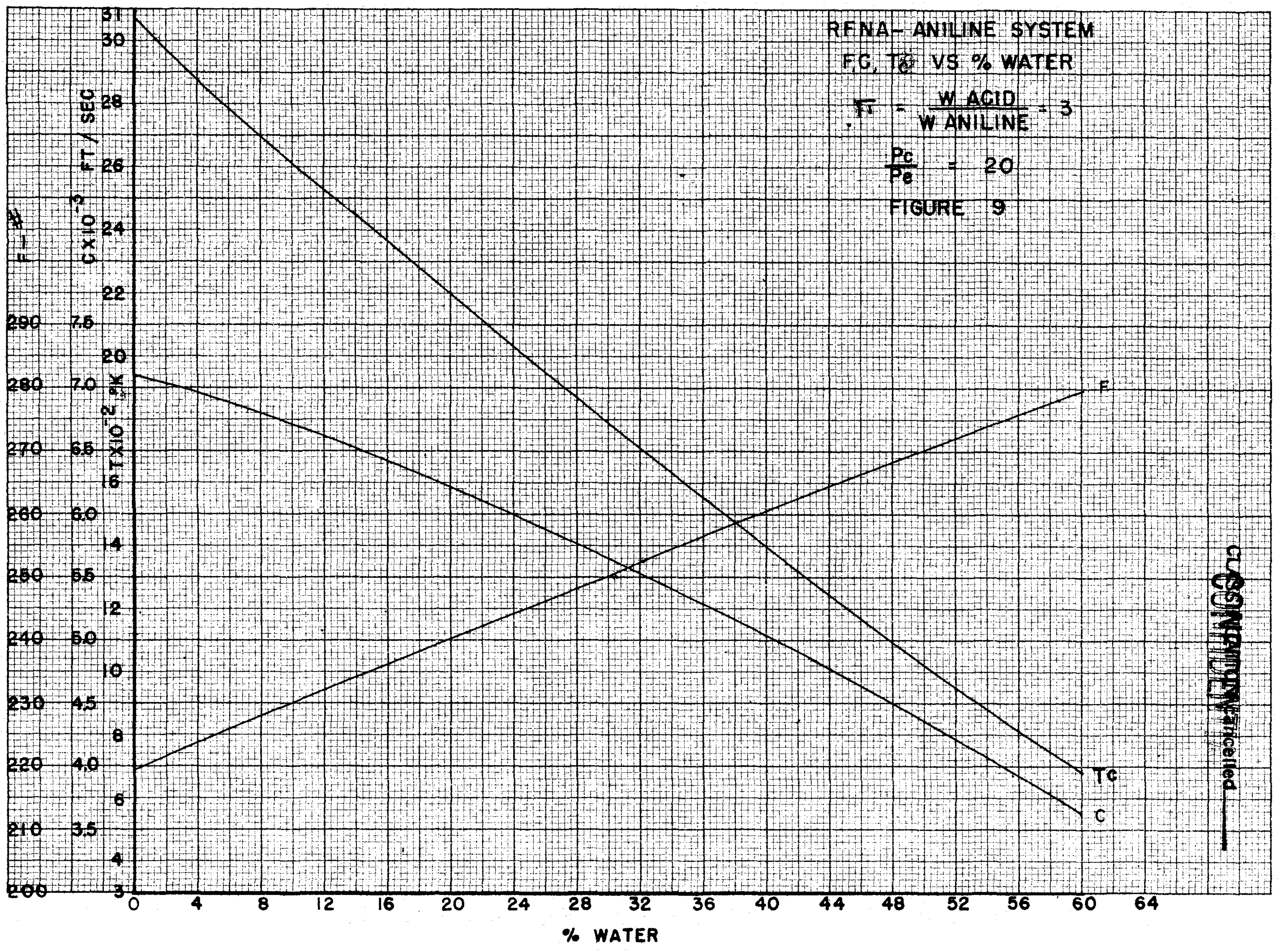

RFNA- ANILINE SYSTEM
F,C, Tc VS % WATER
r = W ACID / W ANILINE = 3
Pc / Pe = 20
FIGURE 9
F
Tc
C
% WATER
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64
T x 10^-2 °K
3 4 6 8 10 12 14 16 20 22 24 26 28 30 31
C x 10^-3 FT / SEC
3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5
F — °F
200 210 220 230 240 250 260 270 280 290

FIG 9

FIGURE 10

STREAMLINED BODY
DEFINED BY EQUATION 6

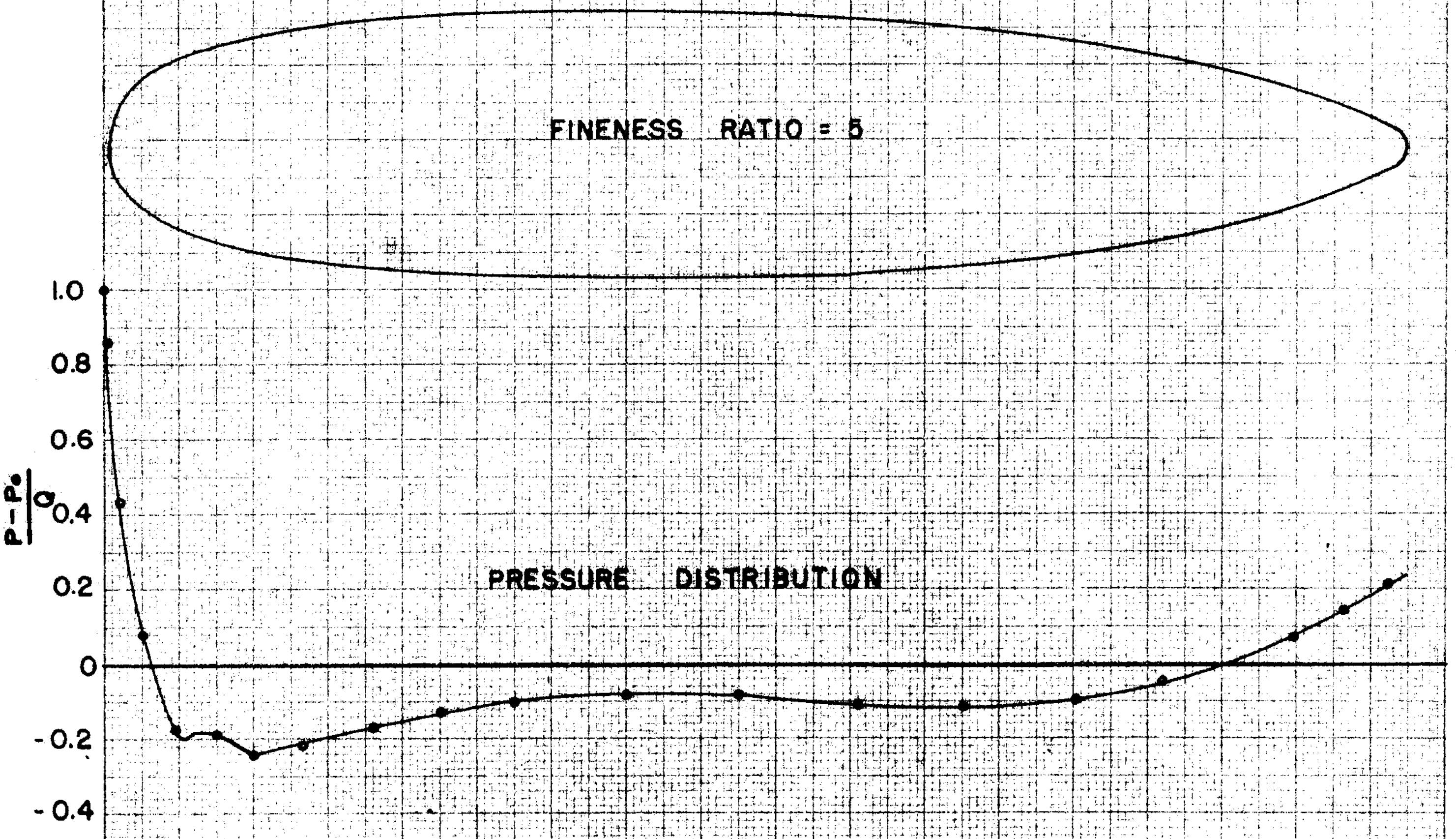
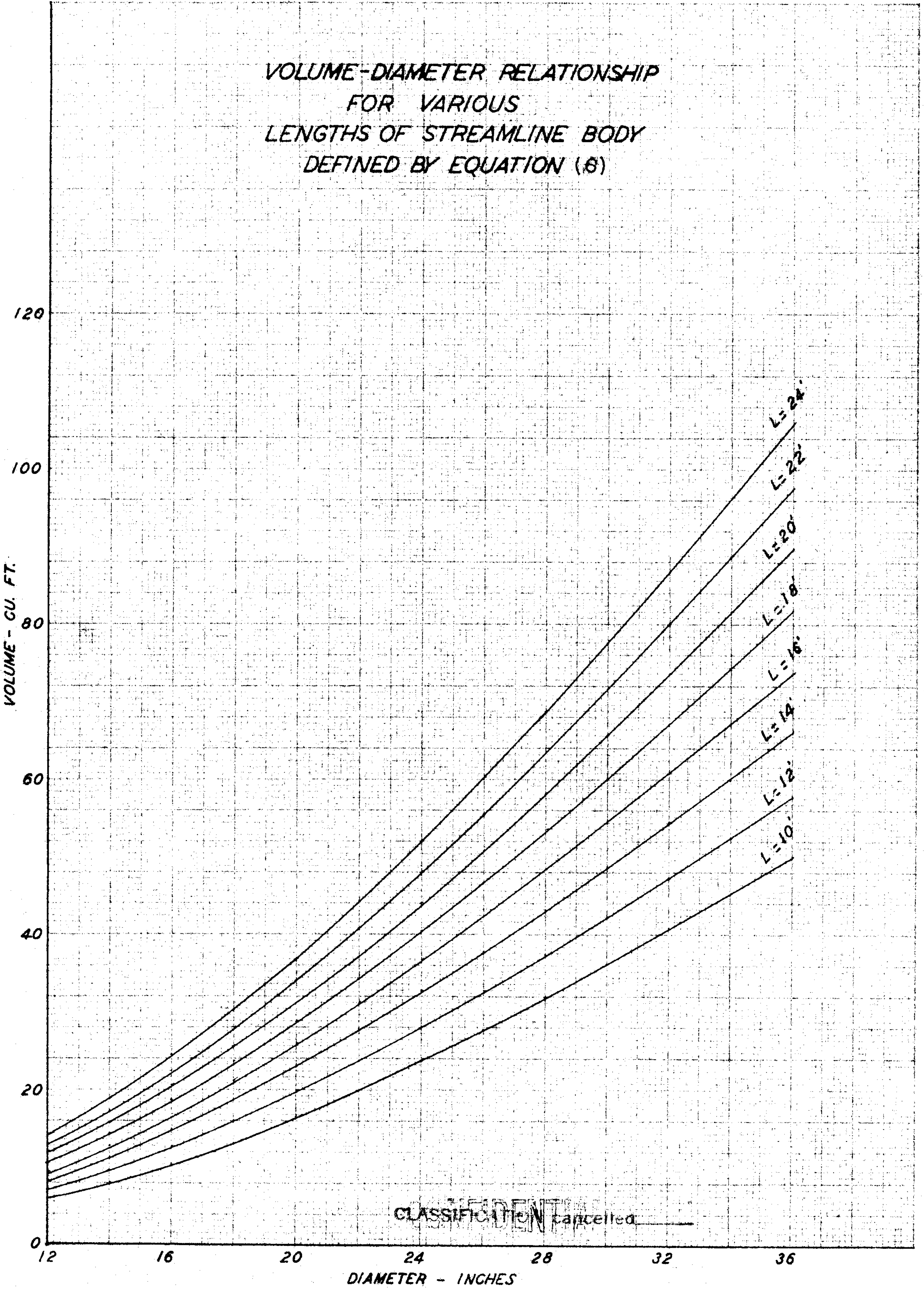
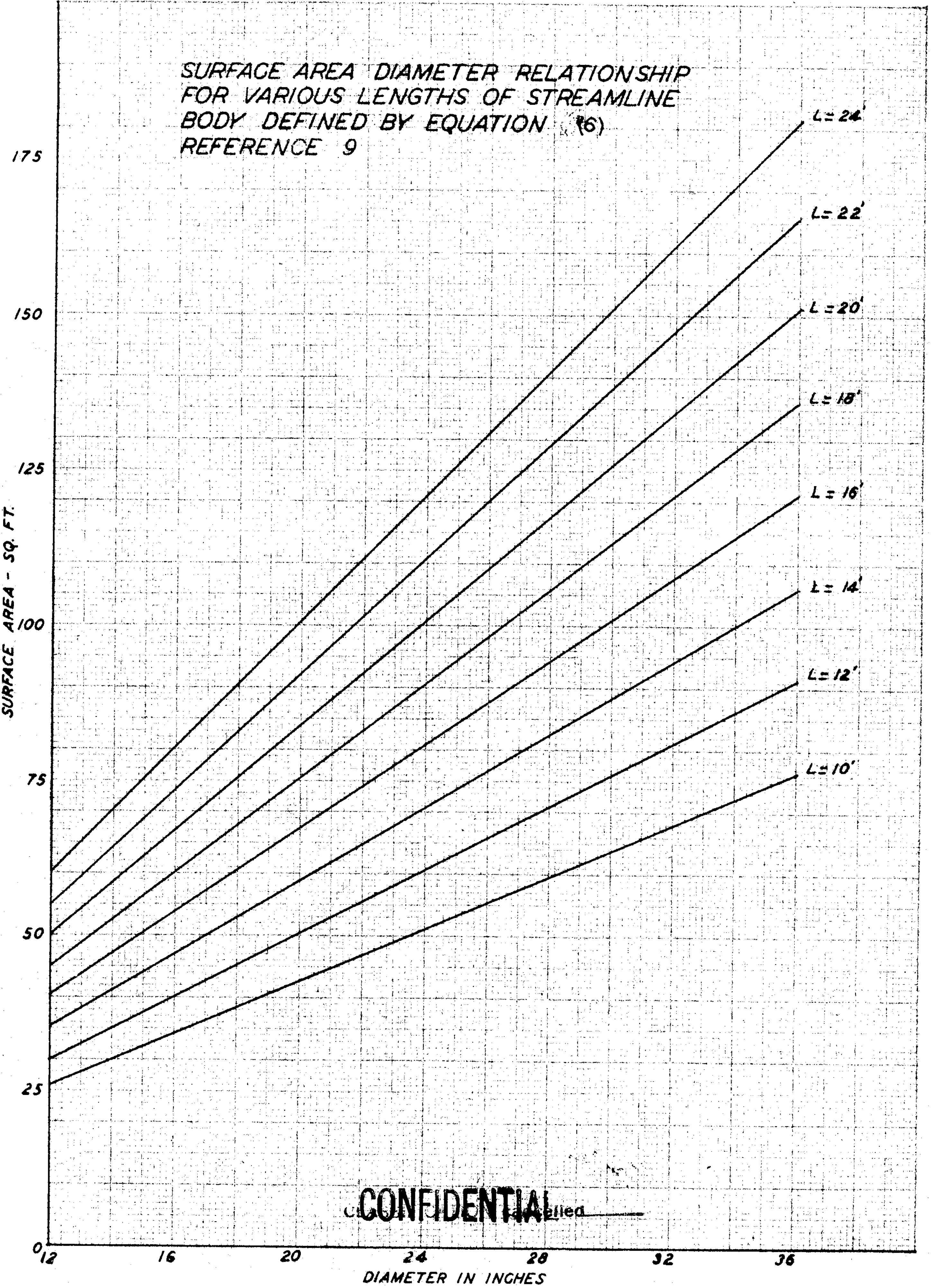


FIG 11



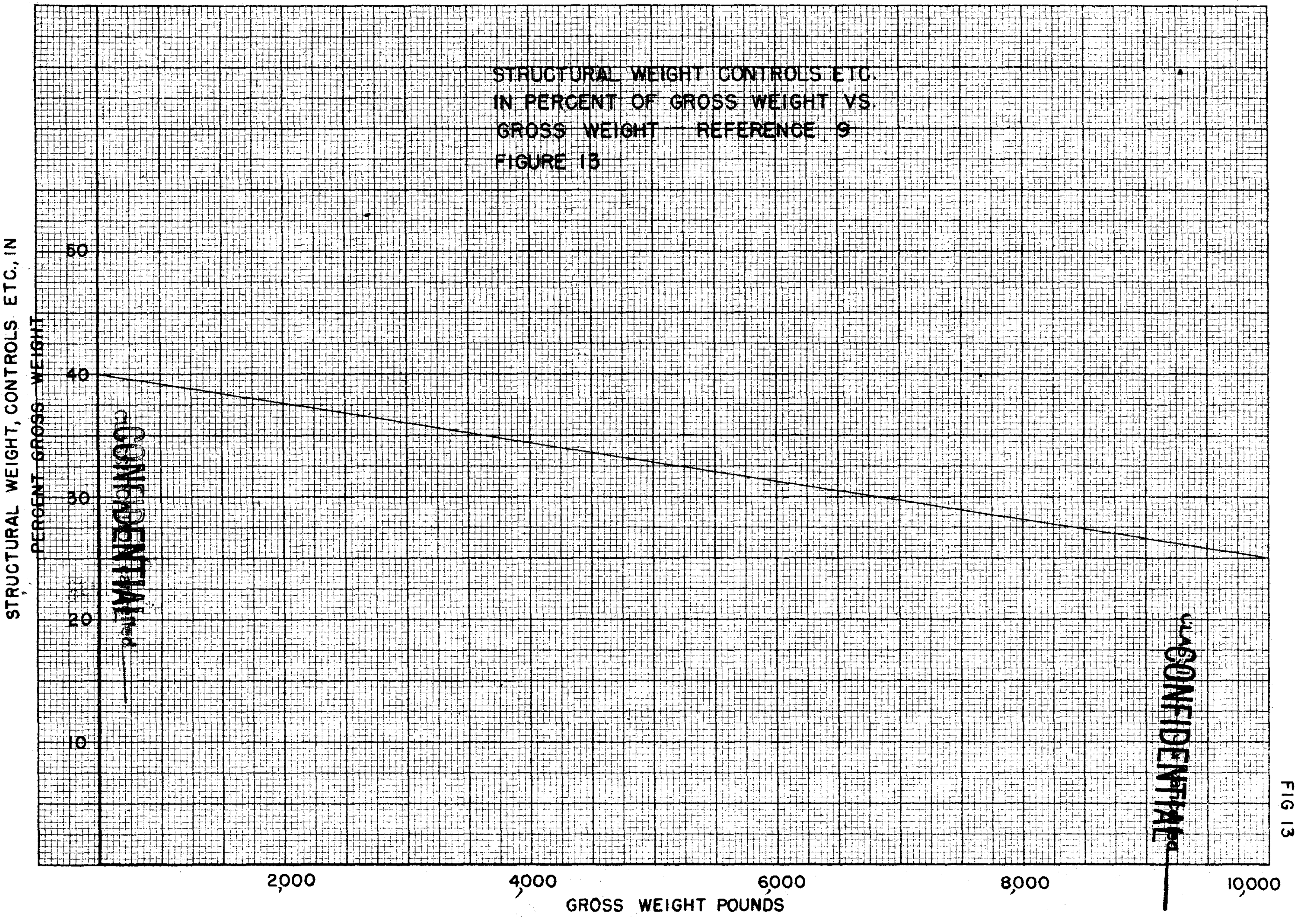
VOLUME-DIAMETER RELATIONSHIP
FOR VARIOUS
LENGTHS OF STREAMLINE BODY
DEFINED BY EQUATION (6)

FIG 12



SURFACE AREA DIAMETER RELATIONSHIP FOR VARIOUS LENGTHS OF STREAMLINE BODY DEFINED BY EQUATION (6) REFERENCE 9

FIG 13



STRUCTURAL WEIGHT CONTROLS ETC.
IN PERCENT OF GROSS WEIGHT VS.
GROSS WEIGHT — REFERENCE 9
FIGURE 13

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CONFIDENTIAL

FIG 14

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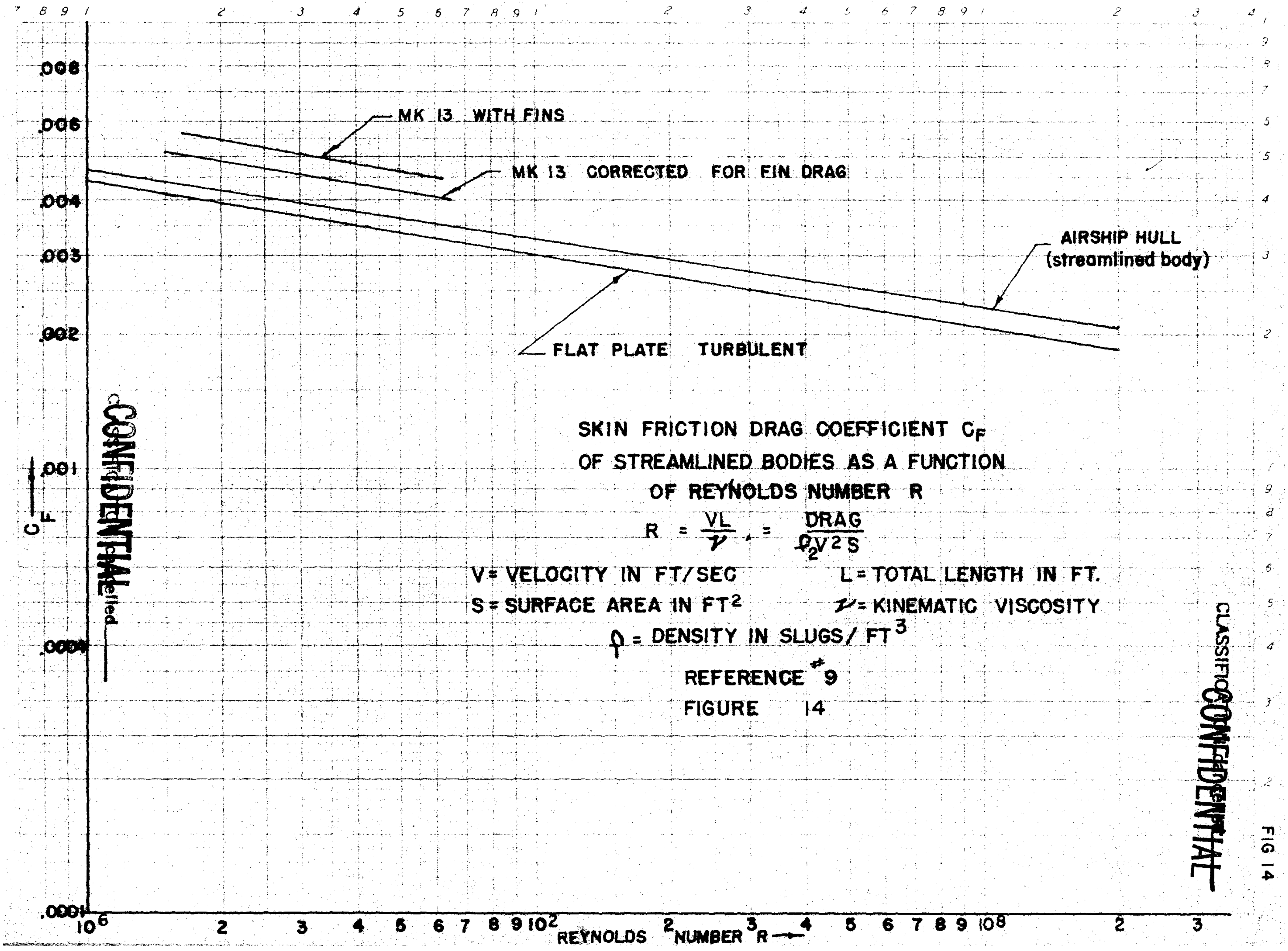

SKIN FRICTION DRAG COEFFICIENT C_F
OF STREAMLINED BODIES AS A FUNCTION
OF REYNOLDS NUMBER R

$$R = \frac{VL}{\nu}, = \frac{DRAG}{\frac{\rho}{2}V^2 S}$$

V = VELOCITY IN FT/SEC

L = TOTAL LENGTH IN FT.

S = SURFACE AREA IN FT^2

ν = KINEMATIC VISCOSITY

ρ = DENSITY IN SLUGS/FT^3

REFERENCE #9

FIGURE 14

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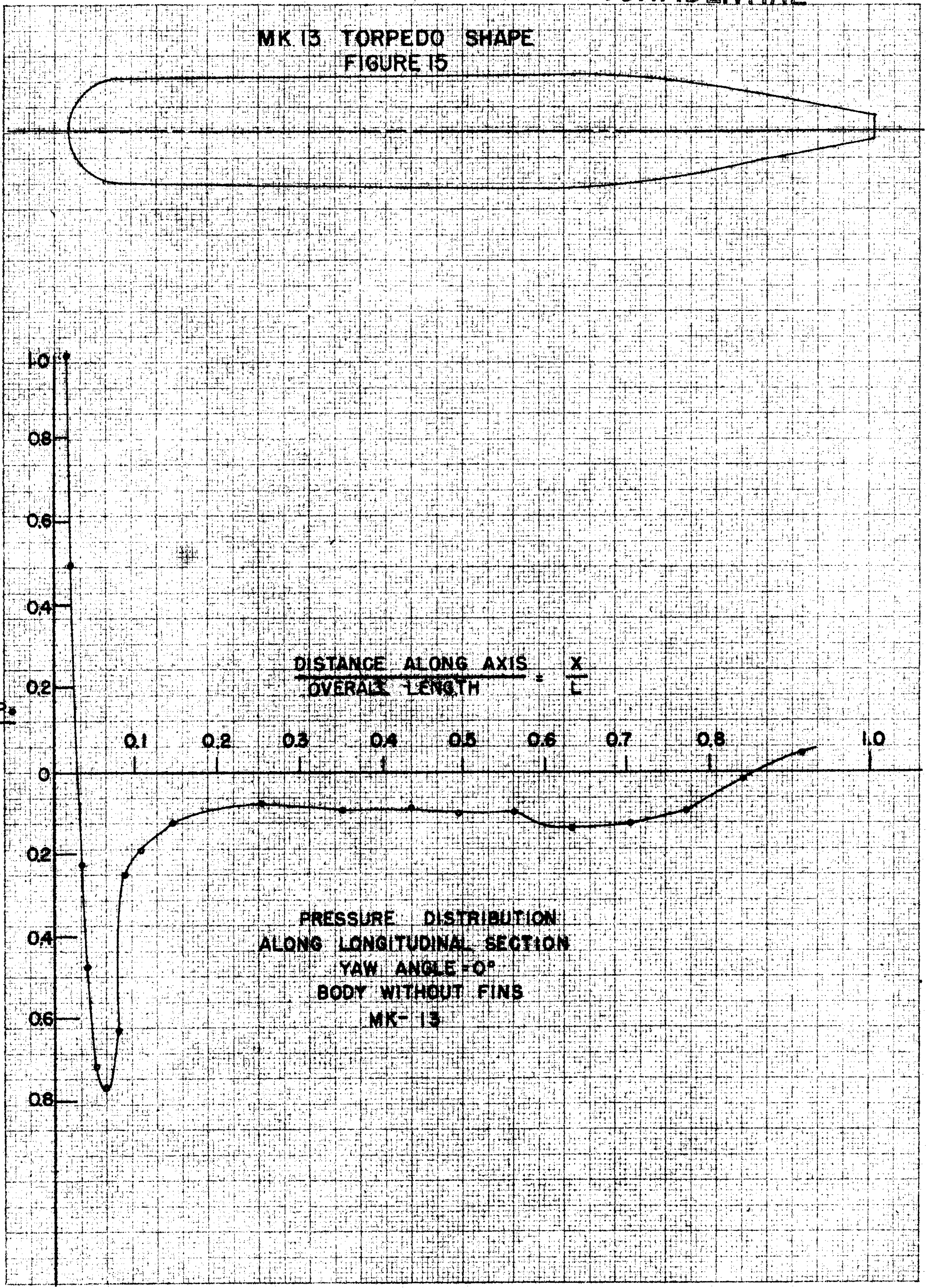

MK 13 TORPEDO SHAPE
FIGURE 15

PRESSURE DISTRIBUTION
ALONG LONGITUDINAL SECTION
YAW ANGLE = 0°
BODY WITHOUT FINS
MK- 13

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CLASSIFICATION cancelled ______

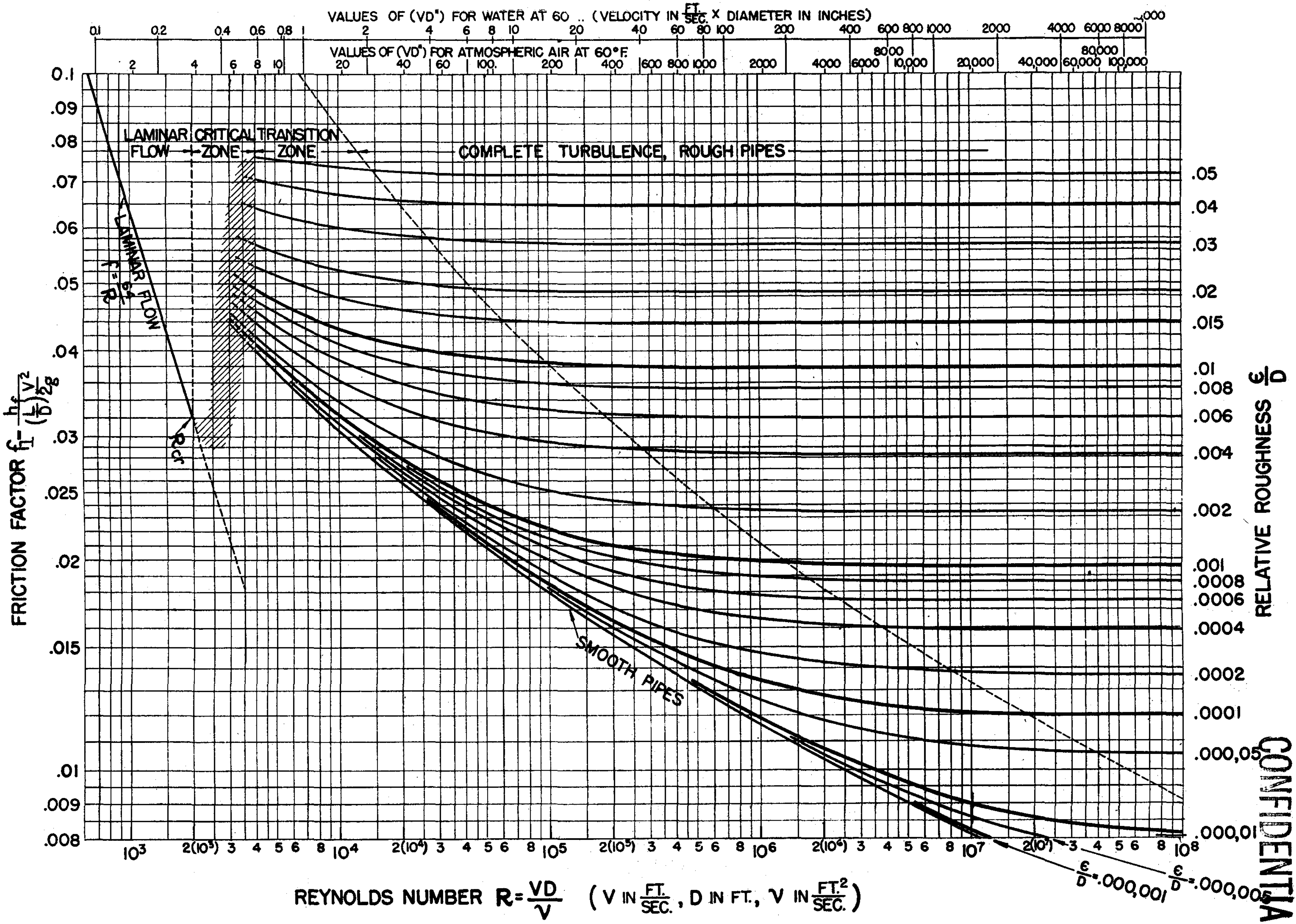

VALUES OF (VD") FOR WATER AT 60 .. (VELOCITY IN $\frac{FT.}{SEC.}$ X DIAMETER IN INCHES)
0.1
0.2
0.4
0.6
0.8
1
2
4
6
8
10
20
40
60
80
100
200
400
600
800
1000
2000
4000
6000
8000
10,000
VALUES OF (VD") FOR ATMOSPHERIC AIR AT 60°F.
2
4
6
8
10
20
40
60
100.
200
400
600
800
1000
2000
4000
6000
8000
10,000
20,000
40,000
60,000
80,000
100,000
FRICTION FACTOR $f = \frac{h_f}{\left(\frac{L}{D}\right)\frac{V^2}{2g}}$
0.1
.09
.08
.07
.06
.05
.04
.03
.025
.02
.015
.01
.009
.008
LAMINAR FLOW
CRITICAL ZONE
TRANSITION ZONE
COMPLETE TURBULENCE, ROUGH PIPES
LAMINAR FLOW
$f = \frac{64}{R}$
R_{cr}
SMOOTH PIPES
RELATIVE ROUGHNESS $\frac{\epsilon}{D}$
.05
.04
.03
.02
.015
.01
.008
.006
.004
.002
.001
.0008
.0006
.0004
.0002
.0001
.000,05
.000,01
$\frac{\epsilon}{D}$=.000,001
$\frac{\epsilon}{D}$=.000,005
10^3
$2(10^3)$
3
4
5
6
8
10^4
$2(10^4)$
3
4
5
6
8
10^5
$2(10^5)$
3
4
5
6
8
10^6
$2(10^6)$
3
4
5
6
8
10^7
$2(10^7)$
3
4
5
6
8
10^8
REYNOLDS NUMBER $R = \frac{VD}{\nu}$ (V IN $\frac{FT.}{SEC.}$, D IN FT., ν IN $\frac{FT.^2}{SEC.}$)

Figure 16

FIG.17

Fig 17. RANGE VS SPEED FOR HYDROJET PROPELLED TORPEDO

GROSS WEIGHT - 5000 LBS
PROPELLENT - $CH_3NO_2 - H_2O_2 - H_2O$
100 % H_2O_2
60.0 % H_2O
F = 301.5 LBS/LB PROPELLENT
WAR HEAD WEIGHTS OF 1000 LBS
1750 LBS & 2500 LBS

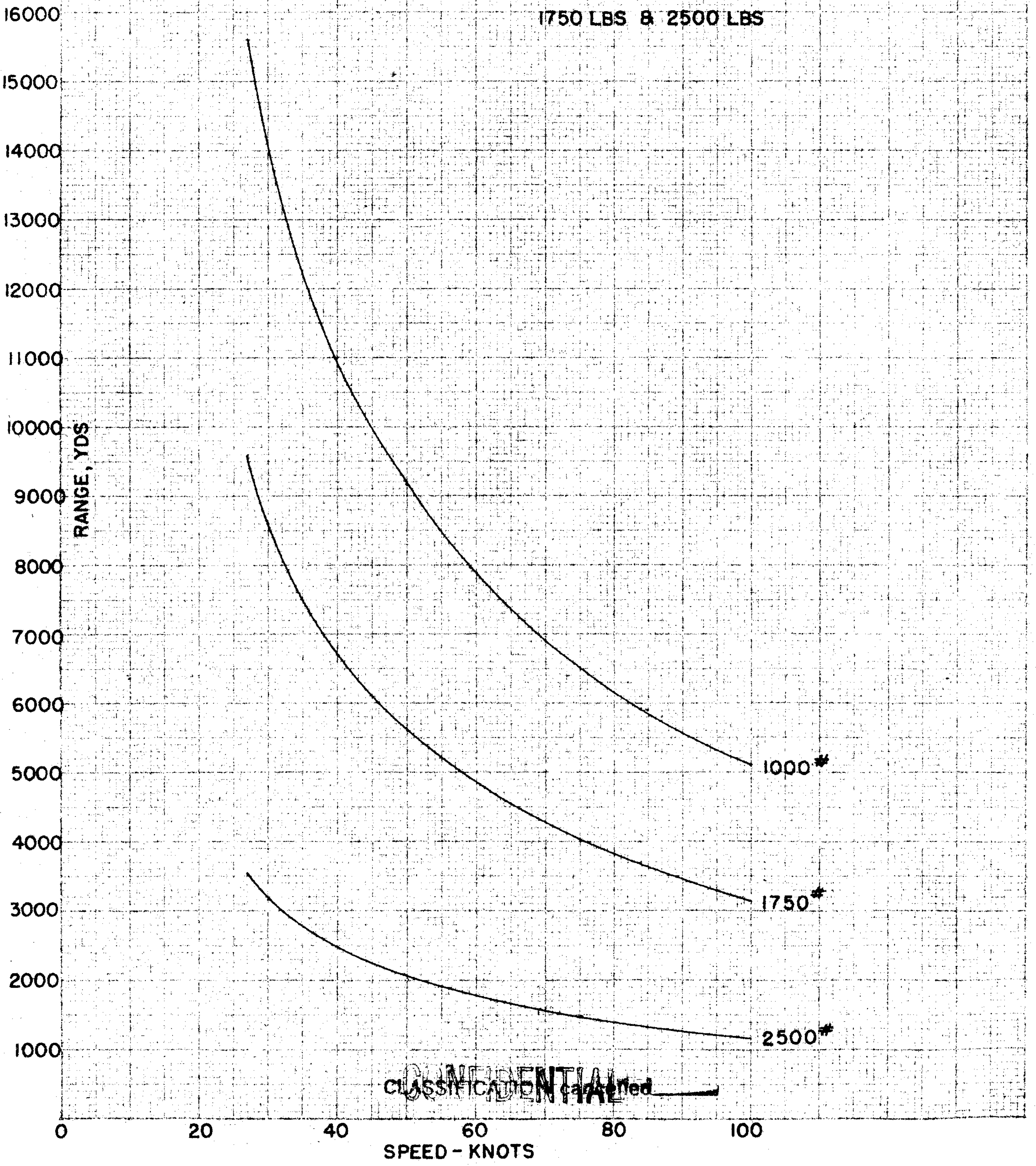
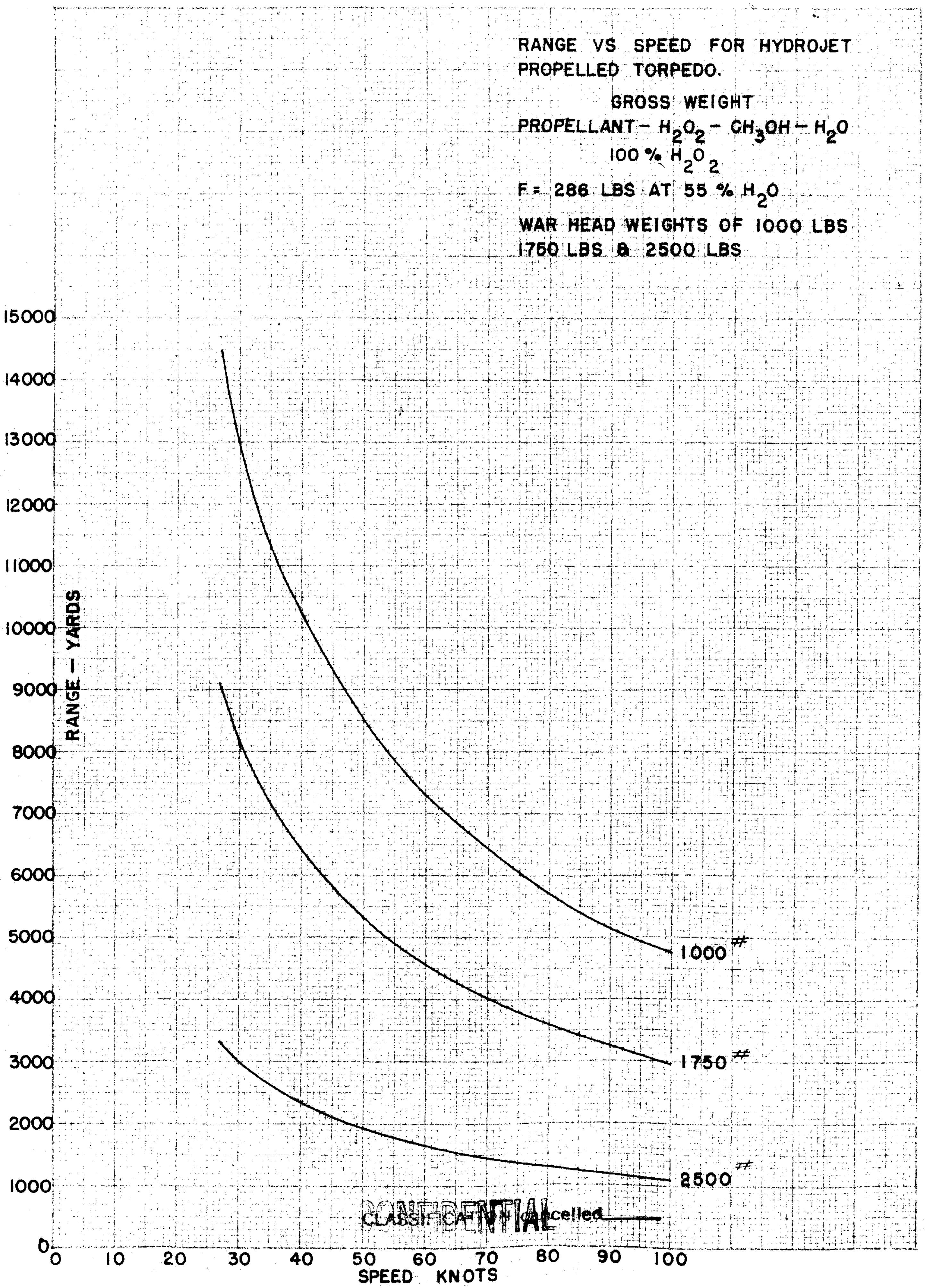


FIG 18



RANGE VS SPEED FOR HYDROJET PROPELLED TORPEDO.

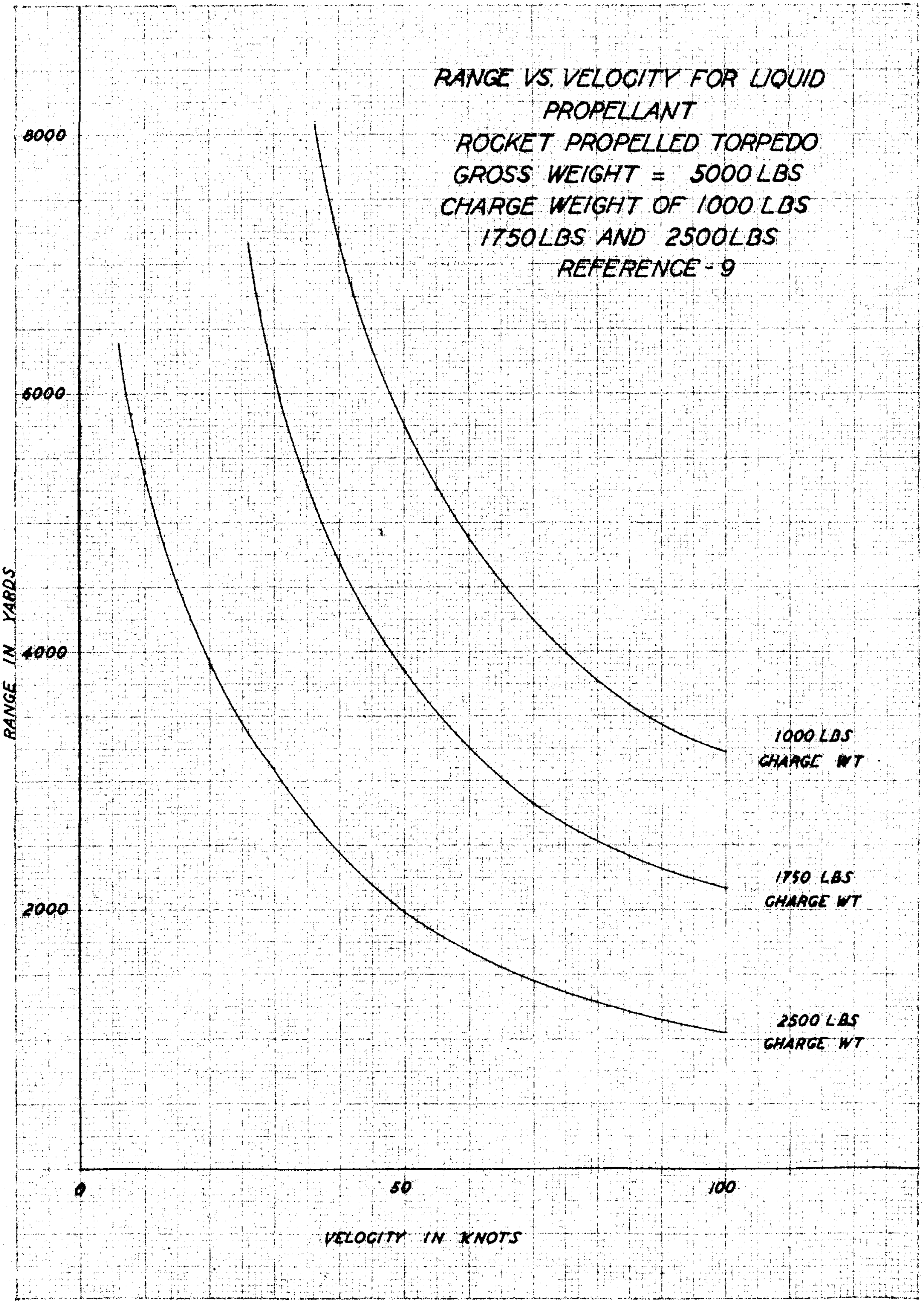
GROSS WEIGHT

PROPELLANT – H_2O_2 – CH_3OH – H_2O

100 % H_2O_2

F = 286 LBS AT 55 % H_2O

WAR HEAD WEIGHTS OF 1000 LBS 1750 LBS & 2500 LBS


RANGE VS. VELOCITY FOR LIQUID PROPELLANT
ROCKET PROPELLED TORPEDO
GROSS WEIGHT = 5000 LBS
CHARGE WEIGHT OF 1000 LBS
1750 LBS AND 2500 LBS
REFERENCE - 9
RANGE IN YARDS
8000
6000
4000
2000
0
50
100
VELOCITY IN KNOTS
1000 LBS CHARGE WT
1750 LBS CHARGE WT
2500 LBS CHARGE WT

Olsen_6-1946

PART	DESCRIPTION	REQ
3-JF-84	ASSEMBLY	
-1	SECONDARY CHAMBER	1
-2	EXHAUST NOZZLE	1
-3	NOZZLE COLLAR	1
-4	NOZZLE EXTENSION	1
2-JF-85	INTER-NOZZLE ASSEMBLY	1
2-JC-80-1	CHAMBER	1
2-JC-80-2	FLANGE	1
1-JC-80-4	SPACER × $\frac{29}{32}$ LONG	1
2-JC-135	INJECTOR	1
2-JC-34-2	CASING	1
1-JC-74-3	CONNECTOR	2
2-JC-36	CASTING BLANK	1
2-JC-37	CASTING BLANK	1
1	NUT - ST'L $\frac{3}{8}$-24NF-3	6
2	WASHER-ALUM.-1 O.D. × $\frac{3}{4}$ I.D. × $\frac{1}{32}$ THK	2
3	BOLT - ST'L $\frac{3}{8}$-24 × 12 LONG	6
4	WASHER - $\frac{3}{8}$ ST'L FLAT	6

LAST DASH NO. -4

2. ASSEMBLE & WELD JC-80-1 CHAMBER & JC-34-2 CASING AS NOTED ON DWG. 4-JC-80.

NOTE: *1. MAY ALSO BE 23.694 OR 29.694 DEPENDING ON LENGTH OF -1 SECONDARY CHAMBER.

Classification Changed to
UNCLASSIFIED
Authority
Ltr TSPIN2C, 1 Dec 45
Date JUN 4 1946 By W J Sanders

10-19-44	Moulton 10-16-44	20 PART 2 TOOL	NOTED			DEVALON 10-6-44	IMUS 10-9-44	10-10-44	RBC 10-10-44	TOLERANCES ± .010 OR 1/64 UNLESS OTHERWISE NOTED FULL
ENG. EXAM.	PROD. EXAM.		MATERIAL	FINISH	HEAT TREAT	DRAFTSMAN	CHECKED	APPROVED	ENGINEER	SCALE / WEIGHT

GALCIT PROJECT No. 1
CONFIDENTIAL
PROJECT No. MX121
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GUGGENHEIM AERONAUTICAL LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

POT ASSEMBLY—
DOUBLE CHAMBER COMBUSTION
NAME

3-JF-84
DRAWING NO.

LATEST CHG. LET.

Figure 20

TABLE 1

INCREASE OF THRUST WITH WATER INJECTION

(Table VIII of Reference 5)

RFNA-Aniline

	No. Tests	r_1	r_2	% H_2O	w' #/sec	F,#	F_N,#	% F	C^*, Ft/sec	w'_{sp}	% w_{sp}	C_F
A	4	3.16	3.51	45.7	1.324	292	234	24.8	7090	.00454	-19.6	1.32
B	4	3.02	3.72	48.0	1.309	283	232	22.0	6970	.00463	-18.0	1.30
C	9	3.01	3.66	47.6	.998	216	177	22.0	6960	.00463	-18.0	1.30
D	6	3.03	4.06	50.0	.763	163	135	20.7	6870	.00469	-17.0	1.31

A throat injecting internozzle $\left(\frac{V_c}{w}\right)_2 \approx 24$

B Rearward injecting internozzle $\left(\frac{V_c}{w}\right)_2 \approx 24$

C Rearward injecting internozzle $\left(\frac{V_c}{w}\right)_2 \approx 33$

D Rearward injecting internozzle $\left(\frac{V_c}{w}\right)_2 \approx 42$

Note:

1. All data are averaged

2. Normal conditions for this scale, reactant mixture ratio, and chamber pressure are:

   $C = 5700$ ft/sec, $w_{sp} = .00565 \frac{\#\ \text{sec}}{\#\ F}$

   $C_F = 1.30 \pm .03$

   Thus $F_N = \frac{w'}{.00565}$ where $w' = w_o + w_f$, or $w - w_d$

3. $\% \Delta F = 100 \frac{F - F_N}{F_N}$, $\% \Delta w_{sp} = 100 \frac{w'_{sp} - w_{sp}}{w_{sp}}$

4. $r_2 = \frac{w_{H_2O}}{w_{aniline}}$

TABLE 2

COMPOSITION OF JPN AND HES 4016 BALLISTITES

Components	JPN, Percentage[1] Composition	HES 4016, Percentage[2] Composition
Nitrocellulose (13.25% N)	51.50	54.0
Nitroglycerin	43.00	43.0
Ethyl centralite	1.00	3.00
Diethyl Phthalate	3.25	0
Potassium Sulfate	1.25	0
Carbon Black	(0.20)	0
Methyl Cellulose	(0.1)	0
Candelilla Wax	(0.075)	0
	100.00%	100.00%

1. "Rocket Fundamentals" - OSRD Report No. 3992, Pg. 119.
2. University of Minnesota Report No. 26, January 9, 1945.

TABLE 3

Maximum Values of F for Chemical Systems

System	F lbs.	Percent Water	Figure	References
H_2O_2 - CH_3OH - H_2O	286.0	57.5	1	1,2,3
H_2O_2 - CH_3NO_2 - H_2O	301.5	60.0	2	1,2,3
CH_3NO_2 - H_2O	256.5	47.0	3	1,2,3,4
H_2O_2 - N_2H_4 H_2O - H_2O	259.0	51.5	5	1,2,3,12
LO_2 - C_8H_{18} - H_2O	405	65.5	6	1,2,3,7
Ballistite - H_2O	302	56.5	7	1,2,3,13,14,15
N_2H_4 HNO_3+$(CH_2)_x$ - H_2O	241.9	48.0	8	1,2,3,11
RFNA-Aniline - H_2O	279.5	60.0	9	1,2,3,5,6

TABLE 4

CHARACTERISTICS OF SOME SERVICE AND PROPOSED TORPEDOES

(Reference 9)

No.	Torpedo	Country	Use	Dea.	Length	War Head Charge	Total Weight	Max. Speed Knots	Range, yds. at speed	Engine type
1.	Mk13	USA	AC	22.4	161	600	2216	33.5	6000	CRT
2.	Mk14	USA	Sub	21.0	246	600	3185	46	4500	CRT
3.	Mk17	USA	Surf	21.0	288	873	4563	46	18000	CRT
4.	Mk18	USA	Sub	21.0	246	600	3042	29	4000	E
5.	MkXII	GB	AC	18	194	432	1591	40	1750	SIC
6.	MkXV	GB	AC	18	194	432	1669	40	2500	SIC
7.	MkVIII	GB	Sub	21	259	722	3354	45	5000	SIC
8.	MkVIIII (IX)	GB	Sub	21	291	727	3731	40	10000	SIC
9.	G7a	Germ.	Sub	21	283	660	3385	44	6600	4R
10.	G7e	Germ.	Sub	21	284	660	3529	30	5500	E
11.	F5	Germ.	AC	17.75	196	440	1626	30	3000	4R
12.	F5U	Germ.	AC	17.75	197	---	1760	40	8700	4R
13.	K-Butt	Germ.	Sub	21	283	---	2380	42	3800	SWT
14.	Stein-B	Germ.	Sub	21	283	---	3700	45	8700	SWT
15.	Type I	Italy	Sub	21.0	283	595	3748	49	4400	8S
16.	1926W	France	AC	15.75	203	313	1479	44	2180	CRT
17.	Type 91	Japan	AC	17.75	203	484	1880	42	3300	8R
18.	Type 93	Japan	Sub	24.0	352	1080	6500	46	20000	2S
19.	Type 97	Japan	Sub	17.75	220	792	2205	48	3500	2S

TABLE 4 (Continued)

No.	Torpedo	Country	Use	Dia.	Length	War Head Charge	Total Weight	Max. Speed Knots	Range, yds. at speed	Engine type
Proposals and Experimental Designs										
20.	USMC Hydrobomb	USA	AC	28	132	1250	3300	70	1000	SPJ
21.	SRED[1]	GB	AC	24	120	600	1400	70	800	LPJ
22.	Sage	USA	AC	22.4	161	---	2100	52	235	LPJ
23.	Aerojet[2]	USA	AC	--	Mk14	---	3485	75	8900	CRT
24.	Aerojet[3]	USA	AC		Mk13-2		2265	60	6210	CRT
25.	Aerojet[4]	USA	AC		Mk13-2		2305	60	8800	CRT

CRT-counter rotating turbine
E-electric motor drive
SIC-semi-internal combustion engine
4R-4 cylinder radial engine
SWT-single wheel turbine
8S-8 cylinder (Straight) engine
8R-8 cylinder (radial) engine
2S-2 cylinder (Straight) engine
SPJ-solid propellant jet motor
LPJ-liquid propellant jet motor

1. B.G. Neal proposal, SRED Ref. 3.
2. Aerojet proposal to BuOrd.
3. Aerojet Report No. 157 (Air forced feed)
4. Aerojet Report No. 157 (Pump feed)

APPENDIX A

Sample Calculation for a Fully Oxidized
Water Injection System

Component	Moles	Q_f, Kilcal/mole	Q_f, Total
H_2O	16	68.37	1093.92
H_2O_2	3	45.20	135.60
CH_3NO_2	2	27.60	55.20
		Total	1284.72
Products			
H_2O	22	57.86	1272.92
CO_2	2	94.45	188.90
N_2	1	0	0
		Total	1461.82

$$w_T = 512$$

$$\frac{w_T}{w_p} = \frac{512}{224}$$

$$= 2.285$$

$$r_2 = \frac{18 \times 16}{102}$$

$$= 2.82$$

$$Q_{available} = \Sigma\, Q_{f_{products}} - \Sigma Q_{f_{reactants}} = 1461.82 - 1284.72 = 177.1 \text{ Kilcal}$$

$$\Delta H_{300}^{1100} = 22(7.211) + 2(9.291) + 1(5.907) = 182.99 \text{ Kilcal}$$

$$\Delta H_{300}^{1000} = 22(6.208) + 2(7.976) + 1(5.118) = 157.77 \text{ Kilcal}$$

$$T_C = 1000 + 100\ \frac{19.33}{25.02} = 1000 + 77.4 = 1077^{\circ}K$$

Assume $T_e = 700^{\circ}K$

$$\Delta H_{300}^{700} = 22(3.380) + 2(4.232) + 1(2.840) = 85.7 \text{ Kilcal}$$

$$\Delta H_{700}^{1077} = 177.1 - 85.7 = 91.4 \text{ Kilcal}$$

$$\overline{C}_p = \frac{91,400}{377} = 242.5 \text{ calories}$$

$$\overline{C}_v = 242.5 - 25(1.986) = 242.5 - 49.6 = 192.9 \text{ calories}$$

$$\overline{\gamma} = \frac{242.5}{192.9} = 1.258$$

$$r_p = \frac{300 \text{ psia}}{28.8 \text{ psia}} = 11.62$$

$$T_e = \frac{T_C}{(r_p)} = \frac{T_C}{(11.62)^{.205}} = \frac{1077}{1.654} = 650^{\circ}K$$

$$\Delta H_{300}^{650} = 22(2.938) + 2(3.625) + 1(2.476) = 74.48 \text{ Kilcal}$$

$$\Delta H_{650}^{1077} = 177.1 - 74.5 = 102.61 \text{ Kilcal}$$

$$\overline{C}_p = \frac{102600 \text{ calories}}{427^{\circ}K} = 240.0 \frac{\text{cal}}{^{\circ}K}$$

$$\overline{C}_v = 240.0 - 49.6 = 190.4 \text{ cal}/^{\circ}K$$

$$\overline{\gamma} = \frac{240}{190.4} = 1.26$$

$$T_e = \frac{T_C}{(r_p)^{\frac{.26}{1.26}}} = \frac{T_C}{(r_p)^{.2065}} = \frac{1077}{1.659} = 650^{\circ}K$$

$$C = \frac{10^5}{30.5} \sqrt{\frac{2 \times 102.6 \times 4.186}{512}} = \frac{10^5}{30.5} \sqrt{1.675} = 4240$$

$$F = 4240 \left(\frac{2.285}{32.2} \right) = 300.5 \,\#$$

APPENDIX B

Sample Computation of an Under Oxidized System Using Acid-Aniline

Reactant		C	H	N	O
$C_6H_5NH_2$	100 gms	6.4434	7.5173	1.0739	---
H_2O	500 gms	---	55.5554	---	27.7777
HNO_3	274.5 gms	---	4.3558	4.3558	13.0674
NO_2	19.50 gms	---	---	.4238	.8476
H_2O	6.00 gms	---	.6660	---	.3330
Total		6.4434	68.0945	5.8535	42.0257

$$\Sigma Q_{f\,\text{reactants}} = 1.0739(-7.338) + 27.771(68.37) + 4.3558(41.658)$$
$$+ .4238(-6.111) + .3333(68.37) = + 2092.86$$

$$(K-1)\,N_{H_2}^2 + \quad (2C - O + H) + (O - C - \frac{H}{2})K_1 \quad N_{H_2} - \frac{H}{2}(2C - O + \frac{H}{2}) = 0 \quad \text{(Eq. A)}$$

$H = 68.0945$ $\qquad (2C - O + H) = 38.9556$

$\frac{H}{2} = 34.0472$ $\qquad (O - C - \frac{H}{2}) = 1.5351$

$C = 6.4434$

$O = 42.0257$ $\qquad (2C - O + \frac{H}{2}) = 4.9083$

Assuming $T_C = 900^\circ K$, $K_1 = .4546$

Solving Equation A with $K_1 = .4546$

$N_{H_2} = 3.4$

$N_{H_2O} = \frac{H}{2} - N_{H_2} = 34.05 - 3.4 = 30.65$

$N_{CO} = (2C - O + \frac{H}{2}) - N_{H_2} = 4.908 - 3.4 = 1.51$

$N_{CO_2} = (O - C - \frac{H}{2}) + N_{H_2} = 1.54 + 3.4 = 4.94$

$N_{H_2} = 2.93$

$Q_{available} = \Sigma Q_{f_{products}} - \Sigma Q_{f_{reactants}}$

$= 30.65\ (57.86) + 1.51\ (26.84) + 4.94(94.45) - 2092.86 = 187.66$

$\Delta H_{300}^{900} = 3.4\ (4.212) + 30.65(5.234) + 1.51(4.386) + 4.94(6.692)$

$+ 293(4.343) = 226.31$

Assuming $T_C = 800^{\circ}K$

$K_1 = .2478$

Solving Equation A with $K_1 = .2478$;

$N_{H_2} = 4.70$

$N_{H_2O} = 29.35$

$N_{CO} = .21$

$N_{CO_2} = 6.24$

$N_{N_2} = 2.93$

$Q_{available} = 29.35(57.86) + 21(26.84) + 6.24(94.45) - 2092.86$

$= 200.34$ Kilcalories

$\Delta H_{300}^{800} = 4.70(3.502) + 29.35(4.292) + .21(3.615) + 6.24(5.441) + 2.93(3.582)$

$= 187.64$ Kilcalories

Interpolating until $H_{300}^{T_C} = Q_{available}$

$T_C = 825^{\circ}K$

$H_{300}^{T_C} = Q_{available} = 197.2$ Kilcalories

Assume $T_e = 500^{\circ}$

$\Delta H_{300}^{500} = 4.70(1.393) + 29.35(1.641) + .21(1.404) + 6.24(1.970) + 2.93(1.399)$

$= 71.40$ Kilcalories

$$\Delta H_{500}^{825} = 197.2 - 71.4 = 125.8 \text{ Kilocalories}$$

$$\bar{C}_p = \frac{125,800}{325} = 386.5 \text{ calories}/^{o}\text{C}$$

$$\bar{C}_v = 386.5 - 43.43(1.986) = 386.5 - 86.3 = 300.2 \text{ calories}/^{o}\text{C}$$

$$\bar{\gamma} = \frac{386.5}{300.2} = 1.29$$

$$T_e = \frac{T_C}{(20)^{.29/1.29}} = \frac{825}{1.962} = 420^{o}\text{K}$$

Assume $T_e = 415^{o}\text{K}$

$$\Delta H_{300}^{415} = 4.70(.800) + 29.35(.936) + .21(.801) + 6.24(1.096) + 2.93(.802)$$

$$= 40.60 \text{ Kil calories}$$

$$\Delta H_{415}^{825} = 197.2 - 40.6 = 156.6 \text{ Kilocalories}$$

$$\bar{C}_p = \frac{156,600}{410} = 382 \text{ calories}$$

$$\bar{C}_v = 382 - 86.3 = 295.7 \text{ calories}$$

$$\bar{\gamma} = \frac{382}{295.7} = 1.288$$

$$T_3 = \frac{T_C}{(20)^{.288/1.288}} = \frac{825}{1.958} = 421^{o}\text{K}$$

$$\Delta H_{300}^{421} = 4.70(.842) + 29.35(.986) + .21(.846) + 6.24(1.158) + 2.93(.844)$$

$$= 42.77 \text{ Kilocalories}$$

$$\Delta H_{421}^{825} = 197.2 - 42.8 = 154.4 \text{ Kilocalories}$$

$$C = \frac{10^5}{30.5}\sqrt{\frac{2 \times 154.4 \times 4.186}{900}} = \frac{10^5}{30.5}(1.2) = 3960 \text{ ft/sec}$$

$$F = 3930\left(\frac{2.25}{32.2}\right) = 274.5 \text{ lbs.}$$

APPENDIX C

Sample Computation of Carbon Deposition
Using Ballistite HE 4016 with 56.5 percent Water Added

$T_c = 844^\circ K$

$T_e = 371^\circ K$

Gas composition at 900°K; $K_C = 2.04$

$N_{H_2} = 12.24$ moles

$N_{H_2O} = 72.75$ moles

$N_{CO} = 1.34$ moles

$N_{CO_2} = 17.54$ moles

$N_{N_2} = 5.485$ moles

$$K_C = \frac{N_{H_2O}\cdot}{N_{H_2} \cdot N_{CO}} \frac{N}{p} = \frac{72.75}{12.24 \times 1.34} \cdot \frac{109.35}{67.5} = 7.19$$

$7.19 > 2.04$, therefore no carbon deposits at 900°K

Gas composition at 800°K; $K_C = 23.3$

$N_{H_2} = 12.79$ moles

$N_{H_2O} = 72.20$ moles

$N_{CO} = 0.79$ moles

$N_{CO_2} = 18.09$ moles

$N_{H_2} = 5.485$ moles

$$K_C = \frac{N_{H_2O}}{N_{H_2} \cdot N_{CO}} \frac{N}{p} = \frac{72.20}{(12.79)(0.79)} \frac{(109.35)}{(67.5)} = 11.6$$

$11.6 < 23.3$, therefore carbon deposits at 800°K

APPENDIX D

Sample Computation of Minor Components
Using the H_2O_2 - CH_3NO_2 System With No Water

Solving the following system of equations simultaneously with the K's given as known functions of temperature, gives the gas composition and chamber temperature listed below .

$$\frac{P_{CO}\,P_{H_2O}}{P_{CO_2}\,P_{H_2}} = K_1$$

$$\frac{P_{NO}\,P_{H_2}}{P_{H_2O}\,(P_{N_2})^{1/2}} = K_3$$

$$\frac{P_{O_2}(P_{H_2})^2}{(P_{H_2O})^2} = K_6$$

$$\frac{(P_{OH})\,(P_{H_2})^{1/2}}{P_{H_2O}} = K_{10}$$

$$\frac{P_{OH}\,P_H}{P_{H_2O}} = K_9\,K_{10}$$

$$\frac{P_{H_2}\,P_O}{P_{H_2O}} = K_7$$

$$C = N_{CO} + N_{CO_2}$$

$$H = 2N_{H_2O} + 2N_{H_2} + N_H + N_{OH}$$

$$O = 2N_{CO_2} + N_{CO} + N_{H_2O} + N_{OH} + 2N_{O_2} + N_O + N_{NO}$$

$$N = 2\,N_{N_2} + N_{NO}$$

Composition of Gases at T_C = 2958°K

N_{H_2}	.321 moles	N_{NO}	.061 moles
N_{H_2O}	5.418 moles	N_{O_2}	.267 moles
N_{CO}	.623 moles	N_{OH}	.347 moles
N_{CO_2}	1.377 moles	N_H	.061 moles
N_{N_2}	.970 moles	N_O	.043 moles

$$\Delta H = Q_{available} = 268.1 \text{ Kilocalories}$$

The exhaust temperature, assuming the above composition to be frozen, was solved for by the trial and error method shown in Appendix A and was found to be 2090°K.

APPENDIX E

SAMPLE COMPUTATIONS OF THE SPEED RANGE CURVES OF A HYDROJET

Torpedo Gross wt. = 5000#, fineness ratio = 10

Propellent System - $H_2O_2 - CH_3NO_2 - H_2O$ (100% H_2O_2)

$F = 301.5$ at 60.0% H_2O

Torpedo volume = 50 ft^3 (Assume Torpedo density of 100 lbs/ft^3)

Charge Weight	2500	1750	1000
Structural Wt. (33%) lbs.	1665	1665	1665
Wt. of motor lbs.	150	150	150
Wt. of pump, gas turbine, gas generator, etc. lbs.	250	250	250
Dry Weight lbs.	4565	3815	3065
Total Propellant Wt. lbs.	435	1185	1935
3% Propellant Wt.	13	36	68
Propellant for propulsion lbs.	422	1149	1867

d = 25"

L = 20.85 ft.

S = 106 $ft.^2$

V Knots	V ft/sec	R x 10^{-8}	C_F	$\frac{\rho S}{2} C_F$	V^2 x 10^{-4}	D	.1D	D_T = D+.1D	$\frac{D_T}{F}$	2500# Warhead			1750# Warhead			1000# Warhead		
										W_p	t_p	R	w_p	t_p	R	w_t	t_p	R
100	169	3.25	.00188	.1982	2.855	5655	566	6221	20.65	422	20.45	1152	1149	55.5	3125	1867	90.4	5090
85	143.8	2.75	.00191	.2015	2.065	4150	415	4565	15.17		27.85	1332		75.8	3630		123.1	5900
75	126.8	2.435	.00196	.2065	1.608	3320	332	3652	12.1		34.9	1475		95.0	4010		154.3	6510
65	109.9	2.11	.0020	.211	1.207	2545	255	2800	9.29		45.5	1663		123.7	4530		201	7360
50	84.4	1.62	.0021	.2215	.711	1575	158	1733	5.75		73.5	2065		199.9	5610		325	9140
40	67.5	1.299	.00217	.2285	.456	1042	104	1146	3.865		109.2	2460		297.5	6690		483	10800
30	50.6	.975	.00228	.2405	.257	619	62	681	2.26		187	3160		509	8590		825	13950
27	45.6	.876	.0025	.264	.208	549	55	604	1.82		232	3130		630	9590		1025	15600

$$\frac{W_{H_2O}}{W_p + W_{H_2O}} = .60$$

$$W_{H_2O} = .60\ W_p + .60\ W_{H_2O}$$

$$.4\ W_{H_2O} = .6\ W_p$$

$$W_{H_2O} = \frac{.60\ W_p}{.40} = 1.50\ W_p$$

at 75 knots

$$W_p = 12.1$$

$$W_{H_2O} = 1.50\ (12.1) = 18.13 \text{ lb/sec}$$

$$\frac{W_{H_2O} \text{ fresh}}{W_{H_2O} \text{ sea}} = \frac{62.4}{64}$$

$$W_{H_2O} \text{ sea} = \frac{W_{H_2O} \text{ fresh} \times 64}{62.4} = 18.62 \text{ lbs/sec}$$

$$W_{H_2O} = A\ v\ \rho$$

$$A = \frac{W_{H_2O}}{v\rho} = \frac{18.62}{64}\ \frac{1}{v} = \frac{.291}{v}$$

Assume $v = 20$ ft/sec

$$A = \frac{.291}{20} = .01455$$

$$d = 12\sqrt{\frac{4A}{\pi}} = 13.52\sqrt{A} = 1.630 \text{ in.}$$

$f = .0150$ (Figure 16)

Assuming 20 foot pipe

$$h_f = .015\left(\frac{20 \times 12}{1.630}\right)\frac{(20)^2}{2g} = 13.7 \text{ ft head lost}$$

$$p_f = \frac{13.7 \times 64}{144} = 6.09 \text{ lbs/in.}^2$$

$$p_T = p_s + 1/2\rho\ (v_o^2 - v_p^2) - p_f$$

$$= 25.8 + .995\frac{(126.8^2 - 20^2)}{144} - 6.09 = 127.9 \text{ lbs.}$$

Use 1.630 inch diameter hole.