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HEATING OF GUNS

by

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HEATING OF GUNS

Abstract

A compendium of heating data for guns ranging in caliber from the caliber .30 rifle to the 105mm A.A. Gun is given. An empirical formula is developed to estimate the heating in any gun. The effect of type of powder on heating is considered. The distribution of energy of the charge is calculated for the caliber .30 and caliber .50 machine guns.

That the barrel of a gun becomes heated during firing is a phenomenon which has probably been observed by everyone who has fired a gun. Quantitative measurements of the heating of small arms rifles were first made by St. Robert in 1870 and of cannon by Noble and Abel in 1875. At that time black powder was still being used as propellant and St. Robert found that from 31.7 to 39.3% of the total energy of the powder charge was used to heat the bore. He also found that the temperature rise was greater proportionately for a single round than for a burst of rounds. This he correctly attributed to the cooling of the barrel by the ambient air during the firing of the burst.

Nobel and Abel found the heat rise of cannon by immersing the gun bore in a water bath and found that from 4.2% to 17% of the powder energy is used to heat the bore. Many experiments have been carried out since but no satisfactory theory has been developed which can explain or duplicate the results obtained.

Empirical Data

The temperature tests which have been conducted at the Proving Ground consisted of firing a gun a certain number of rounds and measuring the temperatures during and after firing. The measurements were made by means of iron-constantan thermocouples welded to certain sections of the gun and connected to a potentiometer-indicator. An example of the measurements taken in a temperature test is given on Plot No. 1.

Data similar to that shown on this plot were obtained for all the firings. The maximum temperature shown is only the measured maximum and it has to be corrected for the cooling during firing. This is done by assuming that the cooling rate shortly after firing ceases, may be used as the cooling rate during firing. In this way the temperature rise per round may be obtained, i.e., the uncooled temperature divided by the number of rounds fired (h - °C/rd).

This "h" represents the average rise in temperature of the wall of the gun at a given place; during the firing of a rapid burst the interface temperature is considerably higher than the surface temperature. In the Appendix to this report a method is developed for determining the temperature difference between the faces.

The heat input per unit area of interface (H) may be obtained from the temperature rise per round, h, by the expression

$$H = \frac{pc(r_o^2 - r_i^2)\ h}{2\ r_i}$$

where the sumbols are defined as follows:

Symbol	Meaning	Units
H	Heat Input	$\text{cal.cm}^{-2}\text{rd}^{-1}$
p	Density of Gun Steel	gm.cm^{-3}
r_o	Outer Radius	cm.
r_i	Inner Radius	cm.
h	Temperature Rise per round	$^{\circ}\text{C rd}^{-1}$
c	Specific Heat of Steel	$\text{cal.gm}^{-1}\,^{\circ}\text{C}^{-1}$

A summary of results obtained by firing guns ranging in size from the caliber .30 to 105 mm A.A. gun is given in Table I on the next page.

It is clear from this table that the heat input in cal. $cm^{-2}rd^{-1}$ is greater in every case but one, near the breech than at the muzzle. In this one case, the caliber .50 machine gun heavy barrel, the rear thermo-couple was very close to the rear bearing and the latter absorbed a significant amount of heat. The increase in heat input at the breech is due, both to the higher temperature of the powder gases and the longer time interval during which the gases are in contact with interface.

However, it has been found that while the heat input is greater at the breech, the muzzle, in many instances, shows a higher rise in temperature. This, of course, is due to the smaller heat capacity near the muzzle because of the smaller outer diameter.

An attempt was made to develop an empirical formula which might be used to estimate the heating of a gun in designing guns. Plot No. 2 shows H, the heating in calories $cm^{-2}rd^{-1}$ against the product of the square of the velocity (feet/sec) by the square root of the caliber (inches). It is evident that there is fairly good correlation between these two functions. An equation was obtained giving this relation:

$$H = 1.0265 \left(\frac{V}{1000}\right)^{2} d^{1/2}.$$

The quantity h ($^{o}C/rd$) is a more useful one in calculating heating effects and is related to H by the following expression

$$h = \frac{2r_i H}{pc(r_o^2 - r_i^2)}$$

where the symbols are defined on page ~~3~~. 2

Combining the two expressions and changing the units to the English system, we get

$$h = \frac{1.62}{(m^2-1)d^{1/2}} \qquad \left(\frac{V}{1000}\right)^{2}$$

TABLE I

TABULATION OF HEATING DATA

Gun	Proj. and Vel.	Dist. from Muzzle (inches)	Outer Dia. (inches)	Max. Temp. Measured $^{\circ}$C	h($^{\circ}$C rd^{-1})	H(cal cm^{-2} rd)	Remarks	
Cal. .30 Tank	172 gr. Ball	3.7	1.21	200-400	1.14	3.04	Nitro-glycerine	Means of
Machine Gun	2600 f/s	11.2	1.21	Maintained	1.55	4.25	Powder	large
		3.7	1.21		1.05	2.81	Nitro-cellulose	series of
		11.2	1.21		1.44	3.92	Powder	rounds
Cal. .50 M.G.	750 gr. Ball	5 1/4	1.5	384	1.36	3.34	Nitro-cellulose powder. One group of 100 rounds and two groups of 199 rounds each with a cooling period of about 15 minutes between groups	
Heavy barrel	2600 f/s	17 1/8	1.87	370	1.26	4.95		
		23 1/2	2.31	314	.89	5.45		
		27 1/4	1.94	322	1.13	4.76		
Cal. .50 M.G. Water-cooled	750 gr. Ball 2600 f/s			100			N-C powder. Two groups of 100 rounds and one group of 198 rounds. External barrel temperature practically constant at temperature of boiling.	
75 mm M1897E3	15.96 lb. Slug	12	4.80	320	1.51	4.55	N-C powder. Group of 300 rounds fired.	
		36	5.28	328	1.40	5.65		
	1755 f/s	55 1/2	5.67	328	1.33	6.54		
3" A.A. T8	15 lb. Slug	12	5.03	352	3.30	11.15	N-C powder. Average of four groups of about 100 rounds each	
	2600 f/s	48	5.86	295	2.39	12.54		
3" A.A. M3	15 lb. Slug	13	5.95	430	2.18	12.0	N-C powder. Group of 247 rounds fired	
	2600 f/s	63	7.28	360	1.59	14.2		
105mm A.A. M1	33 lb. Mod.	12	6.95	285	2.01	9.5	N-C powder. Group of 169 rounds fired in rapid fire test.	
	Slug	88	8.33	303	2.06	16.2		
	2800 f/s	164	9.69	282	1.89	21.g		

where

h is temperature rise in $^{\circ}C\ rd^{-1}$

m is ratio of outer to inner diameter

d is inner diameter (caliber) in inches

v is muzzle velocity in feet sec^{-1}.

This equation gives the average heating of a gun during firing and holds beat for the middle of the bore. All the firings upon which it is based were made with Pyro powder and therefore it holds only for this type of powder.

It should be emphasized that this expression is an empirical one and the results obtained by its application to other calibers can not be relied upon until more data are obtained in support of it.

Effect of Composition of Powder on Heating

In the firing of the cal. .30, two types of powder were used, a double-base (20% NGl) and a single-base (NC). The double base has a higher temperature of explosion than the single base and so its heating effect, too, is somewhat greater. The values of h are given in Table I but are repeated here for comparison.

Dist. from Muzz.	20% NGl	NC
3.7"	1.14°C/rd	1.05°C/rd
11.2"	1.55°C/rd	1.44°C/rd

In the 3" M3 a comparison was made of the effect of using NH and Pyro powder and also of modifying the rotating band by cutting out the center section of copper and leaving .02 flats at the front and rear of the band. The results are given below, expressed in Cal. $cm^{-2}rd^{-1}$.

Rotating Band	Powder	Dist. from Muzzle ft.	$H(cal.cm^{-2}rd^{-1})$
Standard	Pyro	1.08	16.7
Standard	Pyro	5.21	19.3
Modified	Pyro	1.08	14.4
Modified	Pyro	5.21	17.1
Standard	NH(85-10-5)	1.08	13.8
Standard	NH "	5.21	14.6

From the above results, it is seen that the cooler NH powder heats the bore less than the Pyro and that the narrower rotating band also decreases the heating effect.

In estimating the heating of a gun by the formula

$$h = \frac{1.62}{(m^2-1)d^{1/2}} \quad \left(\frac{V}{1000}\right)^2.$$

The result should be increased by 8% if NG1 powder is to be used and should be decreased by 20% if an NH (85-10-5) powder is to be used, so that the above relation becomes:

For NG1 Powder: (20% NG1)
$$h = \frac{1.75}{(m^2-1)d^{1/2}} \quad \left(\frac{V}{1000}\right)^2$$

For NH Powders: (85-10-5)
$$h = \frac{1.30}{(m^2-1)d^{1/2}} \quad \left(\frac{V}{1000}\right)^2.$$

Distribution of Energy of Charge

The distribution of the energy of the charge was determined for the cal. .30 Browning Machine Rifle, Model 1922 and for the two cal. .50 machine guns, the heavy barrel and the water-cooled barrel.

The results obtained from these calculations are given in the following table:

Heat Distribution

	Cal.	.30	Cal.	.50 N.B.	Cal.	.50 W.C.
	cals.	%	cals.	%	cals.	%
Energy absorbed by barrel*	680	23.7	1777	15.7	2600	23.0
Energy absorbed by cartridge case	131	4.6	286	2.5	300	2.7
Energy of bullet	885	30.9	3210	28.3	3320	29.3
Energy of gases (exit vel.)	569	19.9	3060	27.0	3060	27.1
Energy of gases (retained as heat)	600	20.9	3010	26.5	2020	17.9
Total	2865		11343		11300	

* Mr. Kent pointed out that the energy used to heat the barrel is proportional to $V^2d^{5/2}$ while the total energy of the charge is proportional to V^2d^3 (assuming constant efficiency of guns). Therefore the ratio of energy used to heat the barrel to total energy is roughly proportional to the reciprocal of the square root of the caliber ($d^{-1/2}$).

The efficiency of these guns, therefore, ranges from 28.3% to 30.9%, which is better than that obtained in the best of well designed steam engines.

Resumé

It is found that the heating data obtained in temperature tests of guns may be represented for Pyro powder by an expression of the form

$$h = \frac{1.62}{(m^2-1)d^{1/2}} \left(\frac{V}{1000}\right)^2$$

where h is the temperature rise per round at a given cross-section, m is the ratio of outer to inner diameter of that section, d is the inner diameter in inches and V is the muzzle velocity in feet per second. The effect of the energy of the type of powder fired on the constant coefficient in the above equation is discussed.

The difference in temperature of the inner and outer faces of an air-cooled barrel is treated.

The distribution of the energy of the charge of small arms powders is given; the kinetic energy of the projectile is about 30% of the total energy of the charges.

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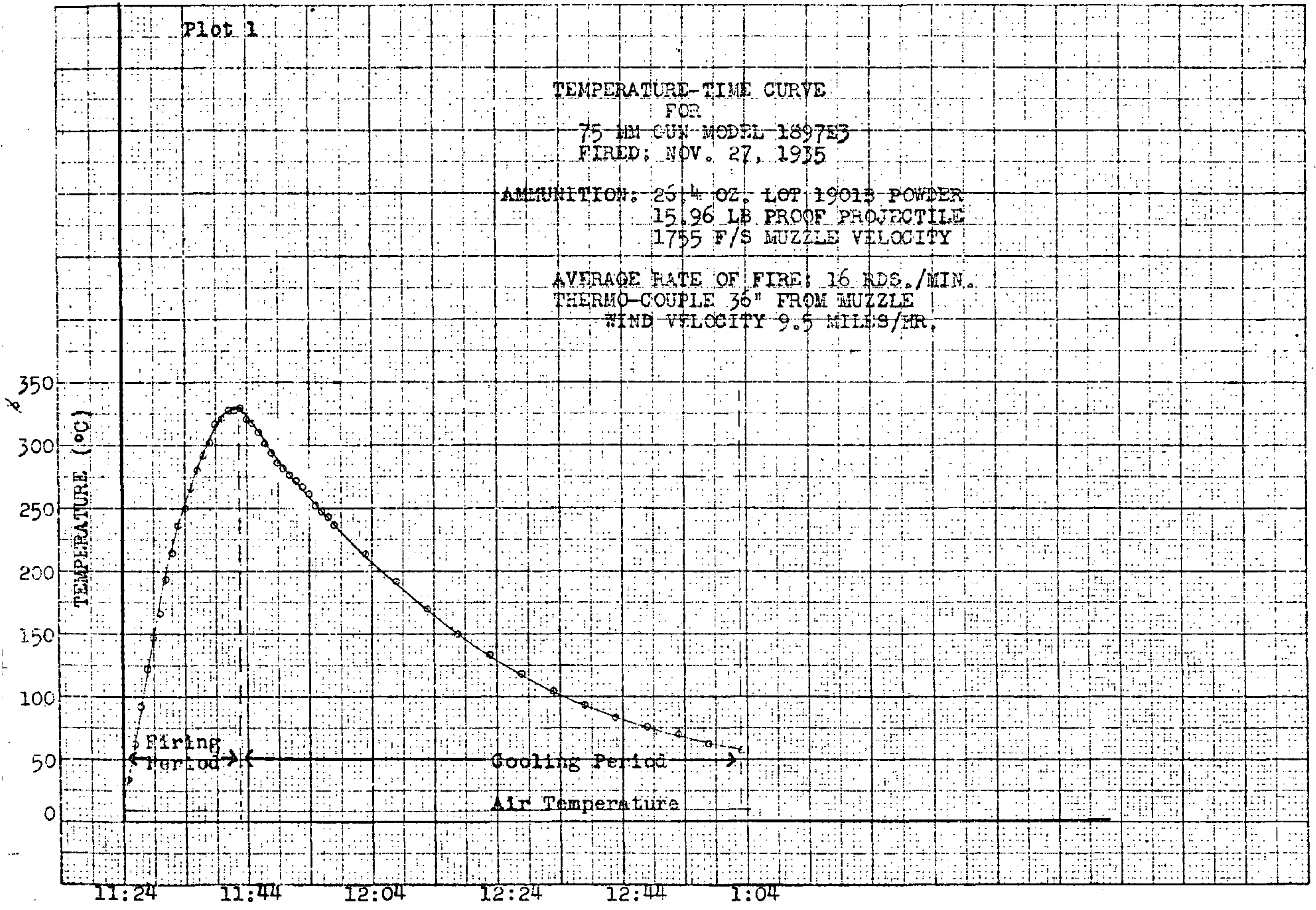
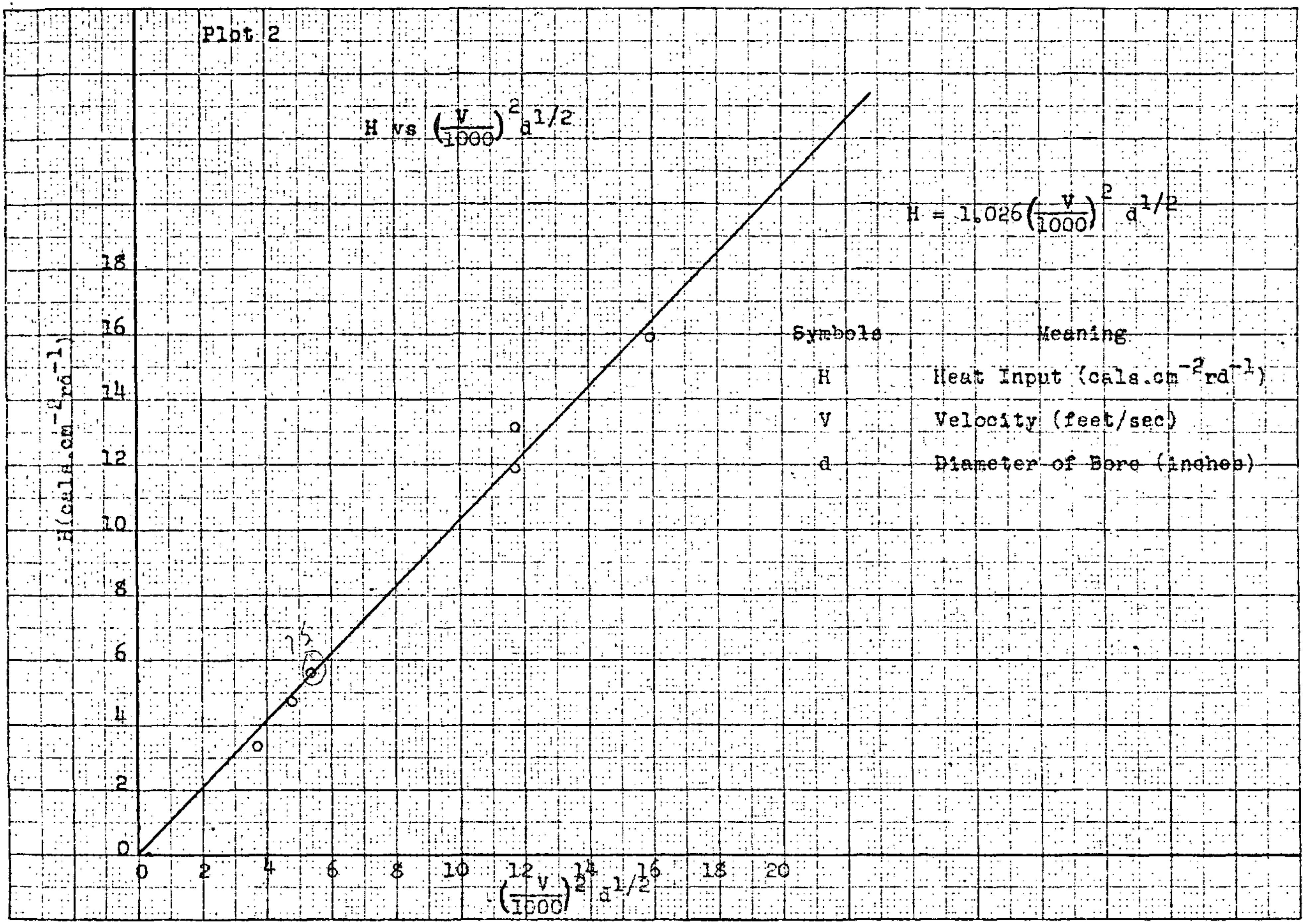


Plot 1

TEMPERATURE-TIME CURVE
FOR
75 MM GUN MODEL 1897E3
FIRED; NOV. 27, 1935

AMMUNITION: 25.4 OZ. LOT 19015 POWDER
15.96 LB PROOF PROJECTILE
1755 F/S MUZZLE VELOCITY

AVERAGE RATE OF FIRE: 16 RDS./MIN.
THERMO-COUPLE 36" FROM MUZZLE
WIND VELOCITY 9.5 MILES/HR.



Symbols	Meaning
H	Heat Input $(\text{cals.cm}^{-2}\text{rd}^{-1})$
V	Velocity (feet/sec)
d	Diameter of Bore (inches)

APPENDIX

Temperature Distribution in An Air-Cooled Gun*

To get the difference in temperature between the surface and interface, it is assumed that the temperature, u, at any point is a linear function of the time, t, i.e.,

$$\frac{au}{at} = A$$

The equation governing the heat distribution in the machine gun barrel is

$$\frac{a\mu}{at} = a^2 \left(\frac{a^2\mu}{ar^2}\right) + \frac{1}{r}\ \frac{au}{ar}$$

where a^2 = thermometric conductivity $(= \frac{K}{pc})$

K = conductivity

p = density

c = specific heat

r = radius of barrel at any given point

A solution of this equation may be shown to be

$$u = At + B \log r + \frac{A}{4a^2} r^2 + C.$$

There are three constants in this equation which have to be determined. Three initial conditions are known and these are given below:

(1) The temperature gradient at the interface

$$\frac{au}{ar} = \frac{B}{r_i} + \frac{A}{2a^2} r_i$$

---

* Temperature of An Aircraft Machine Gun Barrel when fired at a rate of 1200 rds/min.

(2) The initial surface temperature,

$$u_o = B \log r_o + \frac{A}{4a^2} r_o^2 + C$$

(3) The rate of heat input

$$\frac{au}{at} = A$$

Three three initial conditions are determined as follows:

(1) Knowing the heat input per second $(\frac{aH}{at})$, the dimensions of a given section of the barrel, and the conductivity (K), the equation

$$\frac{aH}{at} = - 2nr_i K(\frac{au}{ar})_{r=r_i},$$

enables us to determine the value of $(\frac{au}{ar})_{r=r_i}$

(2) u_o, the initial outside temperature, is assumed to be equal to zero.

(3) $\frac{au}{at}$ is the temperature rise per round (h) multiplied by the number of rounds per second.

The temperature difference between the interface and the surface is

$$\Delta u = u_{r_i} - u_{r_o} = - B \log (\frac{r_o}{r_i}) - \frac{A}{4a^2}(r_o^2 - r_i^2).$$

The mean temperature difference at any point along the horizontal axis of the bore is

$$\frac{1}{v}\int udv,$$

where v is the volume. This may be shown to be equal to

$$\text{Mean } \Delta u = \frac{1}{(r_o^2 - r_i^2)} \left\{ \frac{B}{2} \left[r_o^2(2 \log r_o - 1) - r_i^2(2 \log r_i - 1) \right] + \frac{A}{8a^2}(r_o^4 - r_i^4) + C(r_o^2 - r_i^2) \right\} .$$

By mean temperature difference or mean Δu is meant the mean temperature of the barrel at any point along the horizontal axis, if the surface is assumed to be 0°C.

Calculations:

The calculations described above were made for four guns and the results are given below:

Gun	Rate of Fire	Dist. from Muzzle inches	Temp. Diff. °C	Mean Temp. Diff. °C
75mm	30 rds/min	12	23	6
	"	36	35	9
	"	55 1/2	46	12
3" A.A. T8	30 rds/min	12	59	16
	"	48	91	24
3" A.A. M3	30 rds/min	13	90	23
	"	63	142	33
105 A.A. M1	15 rds/min	12	36	10
	"	88	86	22
	"	164	146	35

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