Essentially, the action of the muzzle gases on a muzzle brake is the same as that of (for comparative and demonstrative purposes) a jet of high pressure steam on the turbine blades of a turbine. The kinematic analysis of each is similar. The gas pressure reduces quickly at the muzzle and the gases escape with a kinetic energy equal to the pressure difference only in the case in which a Laval expansion nozzle is fixed at the muzzle. The gases must pass with a high velocity from the muzzle to the blade (brake). The design of the nozzle must accordingly not impede this flow.

Outflow velocities in the case of simple parallel openings reveal that the critical velocity is far surpassed.

The cross-sectional boundary where the gases are not yet mixed with the air is shown in the accompanying sketch, in graphic scale. This represents the "jet border" within which the muzzle brake must act, also shown in part b of the sketch.

The time that the projectile travels from the muzzle to the brake vane, or blade, is the effective period of the muzzle brake. Gas mass is also significant, so the higher charge-to-mass ratio (c/m) loads are more efficient in muzzle brake action. That is, weapons using ammunition with low charge weights cannot effectively benefit from use of a muzzle brake.

To determine the efficiency of the muzzle brake, fire the weapon at 0° elevation without the muzzle brake, then with the muzzle brake.

As the difference in the lengths of the recoils is only a few millimeters, one can assume in practice that in both cases, with the maximum recoil velocity, the recoil lengths are the same, and that the maximum recoil velocity occurs at the end of the after effect. The brake force K_x may have a constant value.

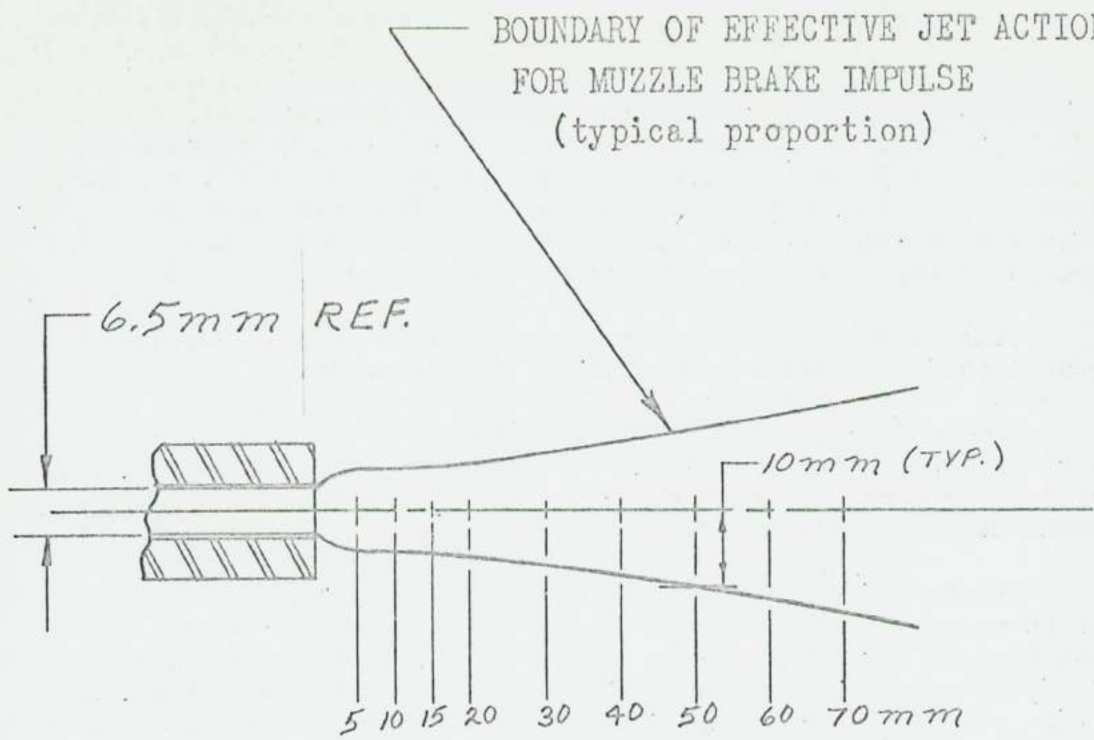
K_x = The constant brake force without muzzle brake,

K'_x = The constant brake force with muzzle brake,

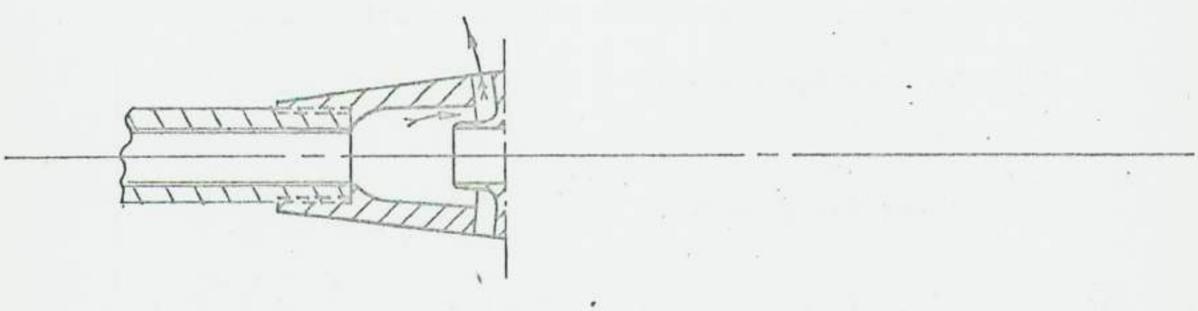
Gr = Weight of recoiling parts.

I. Without muzzle brake: $K_x \cdot S_3 = \frac{Gr}{2 \cdot g} \cdot V^2 \max = E$,

(1) $$K_x = \frac{2 \cdot g \cdot S3}{Gr} \cdot V^2 \max$$



RESULTANT DESIGN OF MUZZLE BRAKE ELEMENT



II. With muzzle brake: $K'x \cdot s_3 = \frac{G'r}{2 \cdot g} \cdot V'^2 \max = E,$

(2) $$K'_x = \frac{G'r}{2 \cdot g \cdot s_3} \cdot V'^2 \max$$

$V' \max \leq V \max$ and in both cases the lengths of the recoils after the after effect are equal because the openings through which the flow takes place are closed only after the end of the recoil. From this it follows that:

(3) $$K'_x < K_x.$$

and the efficiency of the muzzle brake is:

(4) $$y = \frac{E - E'}{E} \cdot (100)$$

Since G_r is almost euqual to G'_r it follows that:

(5) $$y = \left[1 - \frac{V'^2 \max}{V^2 \max} \right] \cdot 100$$

If, also, $s_2 = s'_2$ we may write:

(6) $$E - E' = \frac{Px \cdot s_2}{2}$$

S_1 = Length of recoil, projectile in barrel
S_2 = Length of recoil during the after effect
S_3 = Length of recoil after the after effect

Consequently, the force of the muzzle brake is:

(7) $$Px = \frac{2 \cdot (E - E')}{s_2}$$

Here it was also taken for granted that

$s_2 = s'_2$ and $K_x = K'_x$ (until the end of the after effect)

The Reduction of the Recoil

Without the muzzle brake the total recoil length is:

(8) $$S = s_1 + s_2 + s_3$$

The brake force on the path s_3 is: K_{x3} = Constant

With the muzzle brake the total recoil length is:

(9) $$S' = s'_1 + s'_2 + s'_3$$

The brake force on the path s'_3 is: $K'_{x3} = \text{Constant}$

(10) and $$K_{x3} > K'_{x3} \text{, besides } s_3 \sim s'_3$$

The question now is how great will be the length of recoil ($s''3$) when a muzzle brake is used, if the brake force K_{x3} is the same as without a muzzle brake. We must have:

(11) $$K_{x3} \cdot s''_3 = K'x3 \cdot s'_3 \; ; \quad s''_3 = \frac{K'x3 \cdot s'3}{Kx3}$$

And the reduced length of recoil is: $S_r = s'_1 + s'_2 + s''_3 = s_1 + s_2 + s''_3$ because up until the cessation of the after effect, the recoil lengths are almost the same with and without the muzzle brake. The amount of the shortened recoil is:

(12) $$m = \frac{S - (s'_1 + s'_2 + s''_3)}{S} = \frac{(s_1 + s_2 + s_3) - (s'_1 + s'_3 + s''_3)}{s_1 + s_2 + s_3} =$$

$$= \frac{s_3 - s''_3}{S}$$

Since:

(13) $$s_1 \sim s'_1 ; \; s_2 \sim S'_2$$

VI Weapon Analysis

This is the most critical, constructive, and informative phase of the weapon engineering cycle. Here the designer learns to correct his mistakes, adjust his theories, redesign his mechanisms, and join with others in evaluating performance. The instrumented test vehicle provides time and motion data so that velocites of moving parts are determined, and energy dissipation compared with the weapon cycle.

In this section, the time-displacement camera and resultant capabilities are demonstrated followed by an actual analysis of a recoil operated machine gun under development. Finally, a visual analysis of the Soviet AK-47 assault rifle is given. Firing data and time-displacement records were not available, but the description will reveal a number of features in this design that should be of interest to all small arms design engineers.

Time-Displacement Data

The time displacement record is one of the most useful instruments that a weapon designer can use in the development of an automatic weapons. A typical drum-type T-D camera is shown in the accompanying sketch. With it, the following is determined:

(a.) Motion of selected component of weapon in distance traversed

(b.) Time of component traverse

(c.) Dwell time between shots

(d.) Rate of component traverse during cycle of operations

(e.) Component bounce, if any

(f.) Deflection of mount, or semi-rigid receiver, during firing

(g.) Reproducibility of component travel in a burst of fire

(h.) Rate of fire

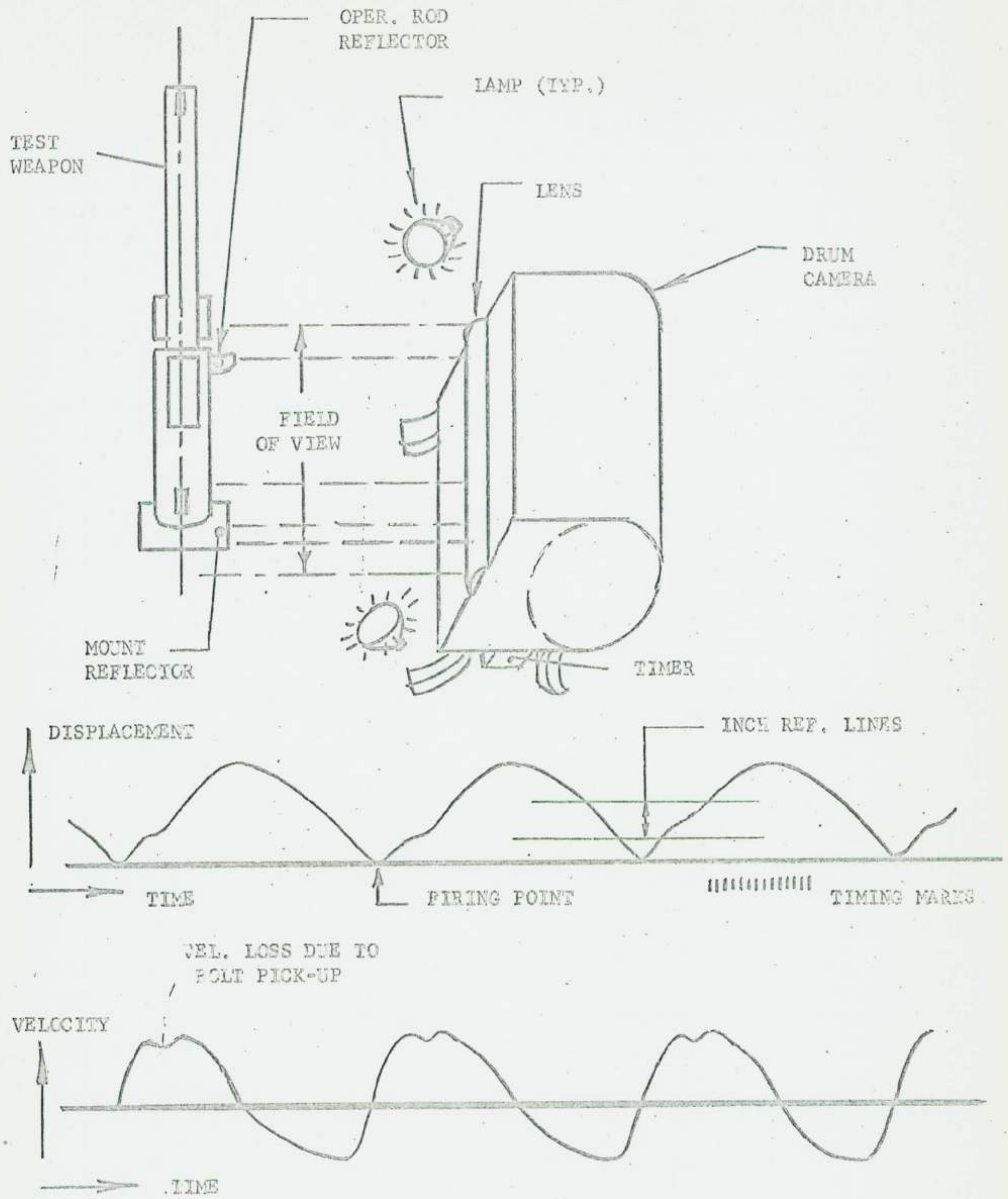
(i.) Time required for mount motion to dampen out.

From the time-displacement curve, the following is derived:

a.) Absolute motion of given component independent of mount deflection,

b.) Velocity of a given component through out its traverse,

TEST WEAPON TIME-DISPLACEMENT DATA



TYPICAL M60 M.G. T-D & T-V DATA - BURST FIRING c.) Acceleration and/or deceleration of the same component,

d.) Energy balance during recoil and counter-recoil motion,

e.) Coefficient of restitution of buffer mechanism.

$$= \frac{Er - Ec'r}{Er}$$

In a typical test, the weapon is mounted in a cradle, or test fixture, and a reflector pin attached to the desired component, say operating rod, and another reference pin mounted on the receiver, or mount. The T-D camera is positioned perpendicular to the weapon, in a brace of spotlights, so that the reference pins reflect light onto the camera's lens.

Within the camera is a 12" dia. rotary drum that will be revolving at a high constant speed at the time of firing. A series of timing marks (indicating milliseconds) will be printed on the roll to indicate the exact speed. A test exposure is made to determine the linear scale, called "inch marks".

On firing, the light reflected from the reference pin will automatically print a curve of operating rod motion with respect to camera drum rotation (time) and a companion curve of mount deflection.

After development of the print, the T-D curve will be a permanent record of the operating rod motion diagram. A brief visual inspection will immediately determine whether or not operating rod motion was smooth and efficient, or "jerky". By viewing with the eye tangent to the curve, discontinuties in motion are readily apparent. Several single shots or a burst of fire may be recorded on a single sheet, so that the slope of the T-D curve can be readily compared for all rounds as well as time span to recoil and counter-recoil motion.

Sudden shifts in slope indicate change in velocity, energy loss, or work done. This is exemplified in the diagram showing recoil motion and attendant velocity diagram of the 7.62mm M60 machine gun. Note how the velocity drops suddenly when the operating rod picks up the relatively heavy bolt and does work in extracting the cartridge case. Then a velocity increase indicates effect of residual chamber pressure (blowback action).

The following data should be marked on one corner of the T-D record for reference:

A) Date of test

B) Weapon model and serial number

C) Number or rounds fired

D) Ammunition lot number

E) Weight of recoiling parts or other components of interest

F) Purpose of test or J.O. #

G) Curve Number

Before evaluating the "operating rod" motion curve, remember that the indicated curve is a result of operating rod motion plus or minus mount motion, depending upon the mount motion diagram. Therefore, a "corrective" operating rod motion diagram must be constructed. This is done as follows:

a) Layout a series of vertical evenly-spaced increments, e.g. .1 inch apart, so that they pass through both the mount motion diagram and the operating rod motion diagram.

b) When both curves are in recoil, subtract the mount motion at each increment from the operating rod motion.

c) When the mount has gone forward past the starting plane then add the mount motion at each increment to the operating rod motion.

The resultant series of points will form the corrected curve of operating rod motion with respect to the receiver. The slope of this curve at any point is the velocity at that point. That is, the tangent of the angle, when correct for time and linear scales, is the operating rod velocity, as follows:

a.) To determine the time scale, measure the length of 20 msec. (21 lines) and divide by 20 (Never use a single spacing)

b.) To determine the linear scale, measure the distance between "inch marks".

c.) Remembering that velocity equals "distance" divided by "time", then:

$$V = \frac{d}{t} = \frac{1/\text{ linear scale} \times 1/12 \tan \theta}{1/\text{time scale}}$$

For example, in a T-D curve where the "inch marks" are 2.03 inches apart, and the "timing marks" are .261 inches apart,

$$V = \frac{1/2.03 \times 1/12 \tan \theta}{1/.261 \times 10^{-3}} = 10.7 \tan \theta$$

$\tan \theta$ = tangent of the curve at any selected point.

d.) Therefore, to obtain a velocity diagram, measure the slope at each increment, and multiply the tangent of the angle by the constant (in this example, 10.7)

To restate the example, calculate the velocity for a slope in which the angle is 45°. The tangent of 45° is 1.0, therefore, this will be the constant that corrects for linear and time scales.

Velocities at any other slope is then merely the tangent of the angle times the velocity calculated for a 45° slope.

If a time-displacement record shrinks or stretches in time, the scale will also move accordingly. Therefore, the record will remain accurate.

An acceleration curve may also be obtained for the operating rod motion as follows:

a.) After laying out the velocity curve, to some suitable scale, say 1" = 10 feet/second and smoothly connecting the points plotted, the slope of the velocity curve is an indication of the acceleration.

An increasing velocity curve shows positive acceleration, while a decreasing velocity indicates deceleration, with attendant forces.

b.) Since $a = v/t$,

$$a = \tan \theta' \times \text{velocity scale} / 1/ \text{time scale} \times 10^{-3}$$

As in the previous example, where in the velocity scale, 1" = 10 fps and in the time scale, 1 msec. = .261 in. This could also be stated as 1" = 3.83 ms, so that the inverse time function would be used in the above formula. $a = \dfrac{\tan \theta' \times 10}{1/.261 \times 10^{-3}}$

$\therefore a = 2610 \tan \theta'$

Therefore the tangent of the observed angle X 2610 = the acceleration at the point observed.

The firing rate is easily calculated by measuring the horizontal distance on the T-D curve from a point on one round to a similar point on the succeeding round and applying the time scale.

This may be done two ways:

a.) measured distance / in/msec. = time,

or b.) measured distance X msec./in = time,

depending upon how the time scale is factored.

In the example noted, "X"/.261 = cyclic time.

Rate of fire = $\frac{60}{\text{cyclic time}}$ (in rpm)

Working from layouts, the positions of key events should be marked on the T-D curves; notably the position where the operating rod picks up the bolt, or where the accelerator works, or where the feed system operates. Knowing the masses involved, then energy used for each function may be determined. This can be compared with energy required to do the work, such as feeding, etc.

As an example, the following data is taken from a study in recoil operated weapons described in Chinn's Vol. IV of "The Machine Gun" pg. 112. Here Time-Travel and Time-Velocity Curves of a Barrel - Accelerator - Bolt function are illustrated.

With the given velocities, Energy values are determined by the formula $E = \frac{W V^2}{2 g}$

Accordingly, the following was determined:

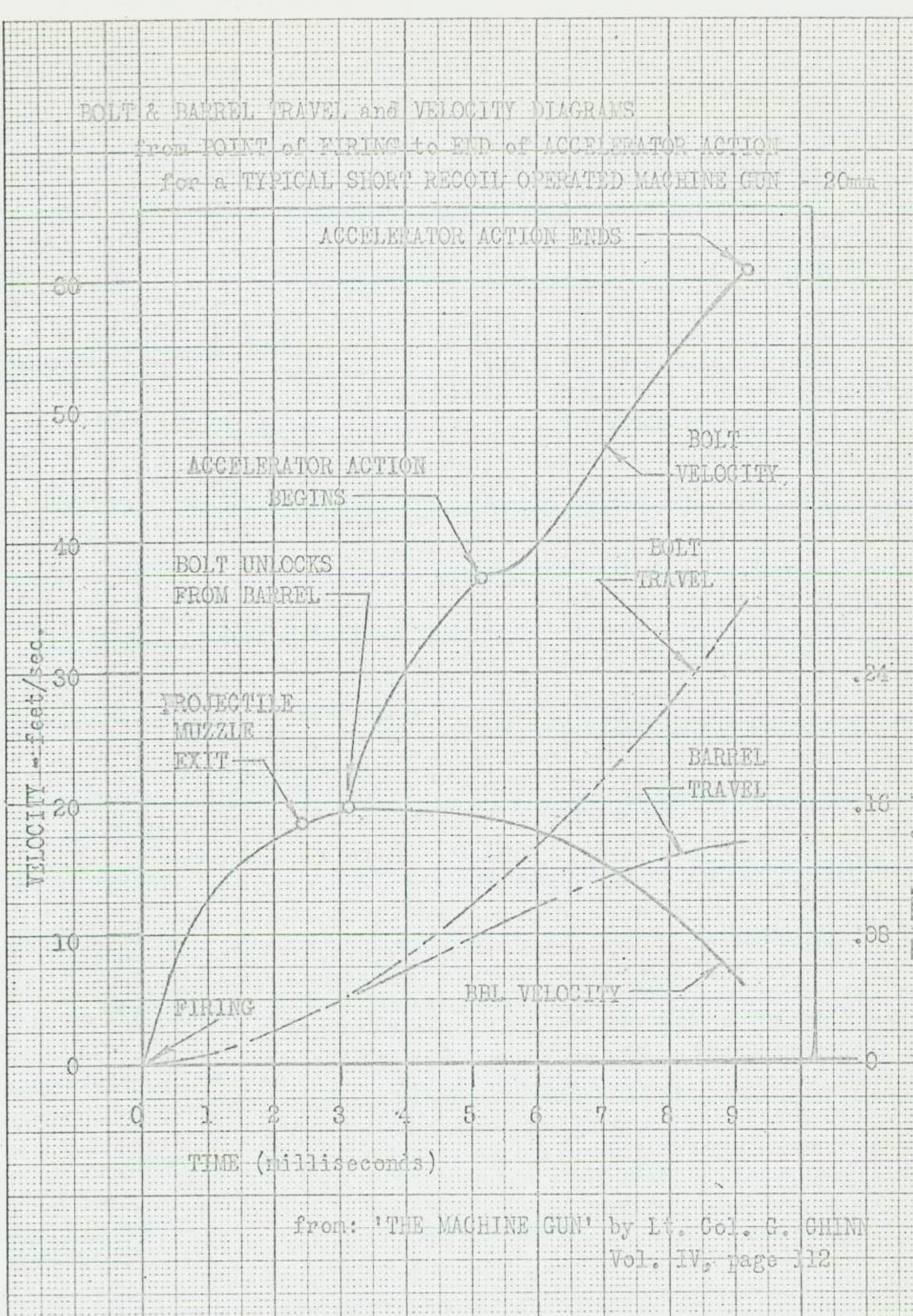
	Bolt, 5 lb.	Barrel, 45 lb.
At Unlocking	18 fps = 25.2 ft. - lb.	18 fps. = 226 ft. - lb.
Start of Acc.	38 fps = 112. ft. - lb.	17 fps. = 202 ft. - lb.
End of Acc.	60 fps = 280 ft. - lb.	7 fps. = 34 ft. - lb.

Thus, the bolt gained 168 ft. - lb. energy while the barrel lost 168 ft.-lb. during the period of acceleration.

Actually, there would be other losses that were not shown here, such as friction, etc.

The bolt energy gain between unlocking and start of acceleration is interesting, and is ascribed to the effect of blowback action.

Translating this theory to the chamber forces, we have the following relationship:


BOLT & BARREL TRAVEL and VELOCITY DIAGRAMS
from POINT of FIRING to END of ACCELERATOR ACTION
for a TYPICAL SHORT RECOIL OPERATED MACHINE GUN - 20mm
ACCELERATOR ACTION ENDS
60
50
BOLT
VELOCITY
ACCELERATOR ACTION
BEGINS
40
BOLT UNLOCKS
FROM BARREL
BOLT
TRAVEL
VELOCITY - feet/sec.
30
.24
PROJECTILE
MUZZLE
EXIT
BARREL
TRAVEL
20
.16
TRAVEL - feet
10
.08
BBL VELOCITY
FIRING
0
0
0
1
2
3
4
5
6
7
8
9
TIME (milliseconds)
from: 'THE MACHINE GUN' by Lt. Col. G. CHINN
Vol. IV, page 112

Given an increase in bolt energy of from 25 to 112 ft. lb. = 87 ft.-lb.

$$I^2 = 2\frac{E\,W}{g} = \frac{870}{32.2} = 26.4$$

$\therefore$ Added Impulse = 5.2 lb.-sec.

time = .002 sec.

Since $I = F\,t$, $F = 5.2/.002 = 2600$ lb.

For the 20mm cartridge, the case dia. (inside) = .9",
Area = .635 $in.^2$ Residual pressure = F/A = 2600/.635 = 4100 psi. As an average pressure, this is reasonable, since the pressure at the muzzle exit is given as 5000 psi.

In summation, the energy calculated for the moving parts should be reasonably traced back to the interior ballistic data for either the chamber and/or gas cylinder.

Analysis of a Recoil-Operated Machine Gun

As a typical example of weapon analysis, consider a 40mm short recoil operated machine gun under development which, in recent firing tests at APG, displayed an undesirably high stoppage rate. This weapon is designed so that in its cycle of operations, all of the required motions are in series, and depend upon mechanical "signals" at the completion of one phase to initiate the following phase in the cycle. This principle was employed to optimize reliability, since the required rate of fire was low enough to facilitate this approach. That is, the weapon cycle would not require two separate mechanisms to function simultaneously. This is particularly desirable in the feed mechanism.

The analysis will correlate the cartridge impulse with the recoil and counter-recoil impulse of the bolt and barrel assembly This will determine whether the principal motive power is being efficiently utilized in operating the weapon. In studying a time displacement diagram, a study of bolt and barrel velocity and energy diagrams will reveal any inefficiencies in the distribution of energy during the weapon cycle.

The cartridge impulse is 13.1 lb.-sec. This is taken from the formula $I = m\,V$, where projectile weight is .532 lb., and velocity averages 790 fps. Gas impulse is negligible, since the powder charge is small, and a high/low pressure system is used.

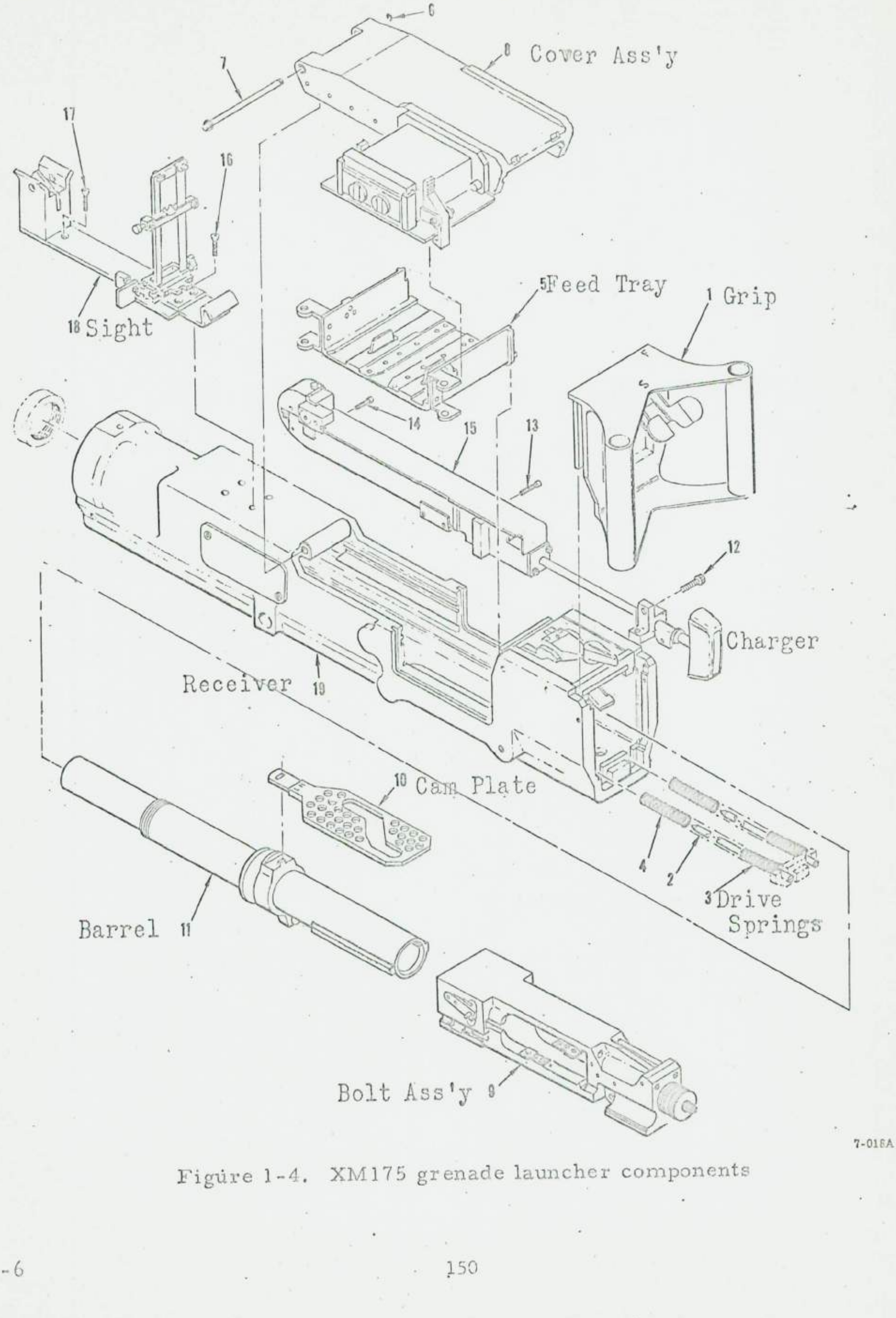


Figure 1-4. XM175 grenade launcher components

Physical data taken from the weapon is as follows:

Barrel assembly weight:	5.07 lb.
Feed cam	.60
Bolt assembly	6.90
Feed slide assembly	1.10

Combined bolt and barrel weight in counter-recoil (with linked round) is 13.50 lb., and in recoil (with linked case) is 13.03 lb.

Accordingly, the impulses were compared. Counter-recoil impulse is 2.9 lb.-sec. and recoil impulse is 10.3 lb.-sec. for a total of 13.2 lb.-sec. which is in agreement with the cartridge impulse of 13.1 lb.-sec. Velocities were determined from averaging a series of time displacement curves as shown. C'recoil velocity is 7.0 fps, while recoil velocity is 25.48 fps.

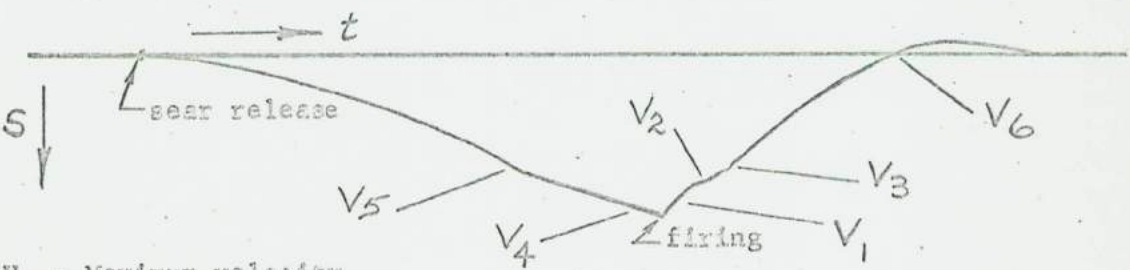
The data from these T-D curves was found to be quite regular from shot to shot, and is as follows: (V_1 to V_6 indicates velocities at principal locations in the cycle) (shown below)

One time displacement curve was analyzed in detail and segmented into 52 increments to show displacement, velocity, and remaining energy for the full bolt-barrel traverse.

The energy loss where the bolt picks up the barrel during counter-recoil traverse is obvious, and indicates inefficiency in the relationship between barrel unlatching and bolt locking.

Schematic of T-D Curve

The velocities and times noted are as follows:



V_1 = Maximum velocity
V_2 = Sudden velocity loss
V_3 = Resumption of velocity level
V_4 = Approaching firing
V_5 = Bolt approaching barrel pickup
V_6 = Bolt approaching sear line
tc'r = time from sear release to firing
t recoil = time from firing to bolt hook-up on sear
t feed = feed time, taken as 38 msec if not available on T-D curve, so that a comparable cyclic rate can be determined.

Curve	VI	V2	V3	V4	V5	V6	t c'r	t rec	RATE
#4	25.3 fps	18.5 fps	21.8 fps	7.1 fps	10.1 fps	6.07 fps	83.6 ms	57.7 ms	335 rpm
#5	24.9	18.5	21.9	7.5	11.3	7.7	80	55	347
#6	was a 5 round burst as follows:								
6a	26.	18.7	22.6	6	7	8.1	105	50	339
6b	25.7	18.5	22.6	7.4	10.5	9.9	82	48	350
6c	25.7	19.	22.6	7.3	10.8	10.3	85	47	340
6d	25.7	18.7	22.4	7.2	10.1	10.7	85	46	360
6e	26	19	22.4	7.3	10.7	11.2	83	46	
#3	26.5	17.4	21.5	7.1	10.5	6.6	85	62	325
#2	25.1	17.6	21	6.7	indistinguishable				
#1	23.9			6.5	"				
Avg.	25.5	18.4	22.1	7.0	10.1	8.8			342

Note: curve [illegible] is the sample detailed in diagram [illegible]

The sharp velocity and energy fluctuations at points 31 and 32 where the feed cam is shifting from a 28° slope to a 43-1/2° slope are most irregular.

The rapid energy decline at points 41 and 42 indicate binding of the bolt in the receiver during recoil.

Feed spring loads were taken as well as feed cocking cam measurements and the feed lever crank ratio. The feed springs have an assembled load of 16 lb. and a rate of 12 lb./inch for each of the two springs. The cam has a dual camming slope of 28° for 1/3 of its stroke, then a slope of 43-1/2° for the remaining 2/3 stroke. The feed lever has a cam arm of 2.2 inches and a feed slide arm of 4.3 inches for a ratio of 1.95.

During recoil, the feed mechanism is cocked by the above cam and arm. The feed slide is spring powered, and remains cocked until the bolt is fully opened. The bolt then signals the feed slide to begin feeding. The bolt remains opened until the feed slide completes its stroke, then the feed slide signals the bolt to begin its chambering and firing stroke (in counter-recoil).

Time-displacement records show that the bolt bounces after it signals the feed slide. Therefore, the cartridge is not properly fed and a stoppage occurs.

The coefficient of energy return by the bolt buffer is .60, and could be improved to .80 by use of a hydraulic buffer. The bolt bounce is also augmented by drive spring surge. This can be alleviated by the use of stranded wire drive springs.

A study of the feed cam design is necessary because of the unusual behavior of the barrel velocity curve, cam profile, and resultant feed slide velocity diagram.

The feed slide is subjected to an unusually high acceleration at the point where the cam changes slope. The velocity changes from 25.5 fps to 42.6 fps in .3 milliseconds. This results in an acceleration of 57,000 fps^2, so a high reaction load will occur.

$F_1 = m\,a = 1.1X57{,}000/g = 1950$ lb.
$F_2 = 1950 X 1.95$ (lever arm ratio) $=$ 3800 lb.

Accordingly a simple modification of the cam path, to eliminate the sudden change in slope is recommended.

This is a radius tangent to the initial 28° slope. While this is not optimum, it frees the feed mechanism of the high acceleration loads.

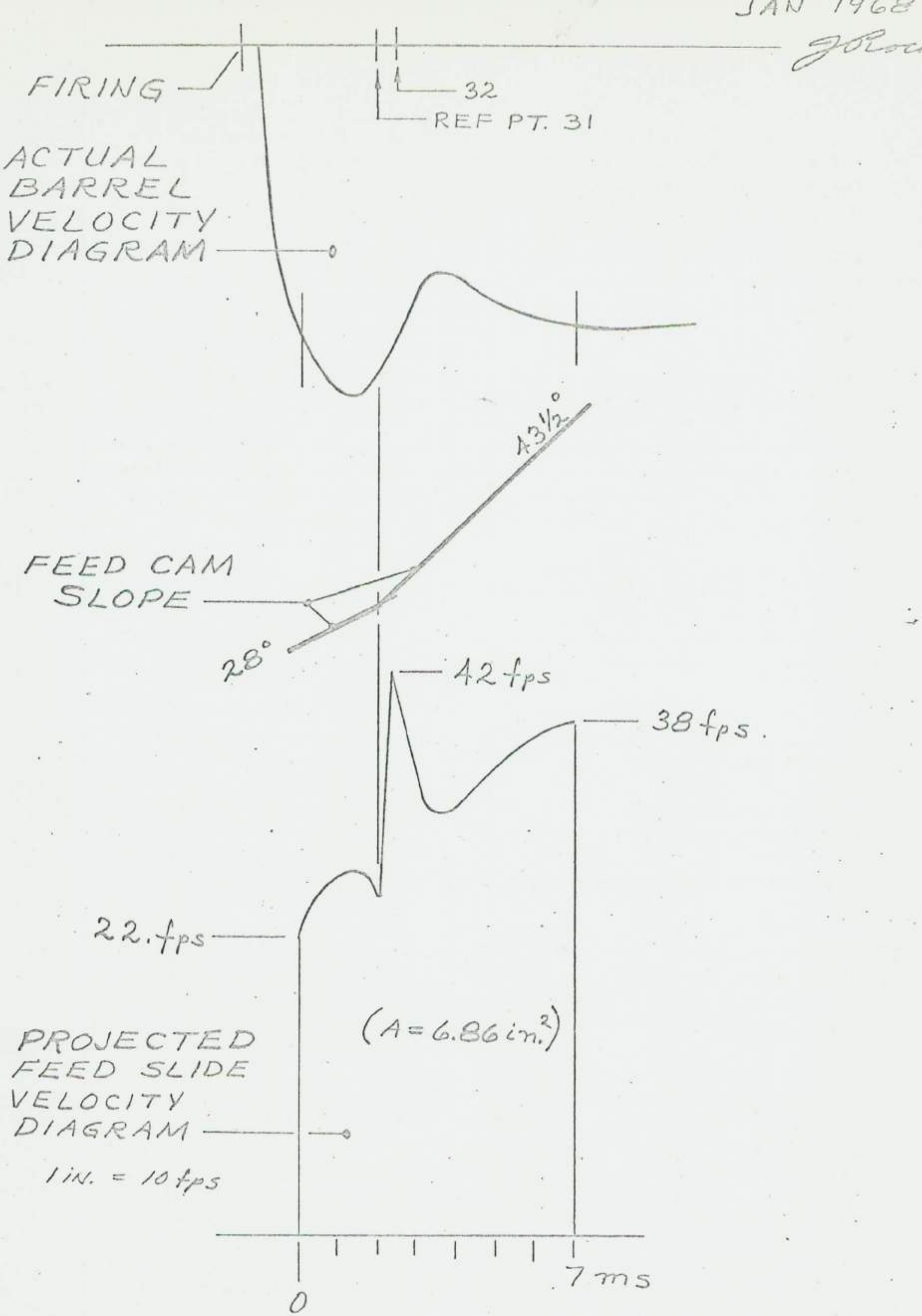
A complete redesign of the cam is in order, and a cycloidal cam is recommended, of the form:

$$\text{displacement} \quad Y = \frac{h}{\pi} \left(\emptyset - 1/2 \text{ SIN } 2\,\emptyset\right)$$

The cycloidal cam has the lowest vibration, wear, stress, noise and shock. The reason for its excellent performance is that there is no sudden change in acceleration at the intersection of the dwell periods and the rise curve. It is also easy starting and the side thrust of the translating follower is low.

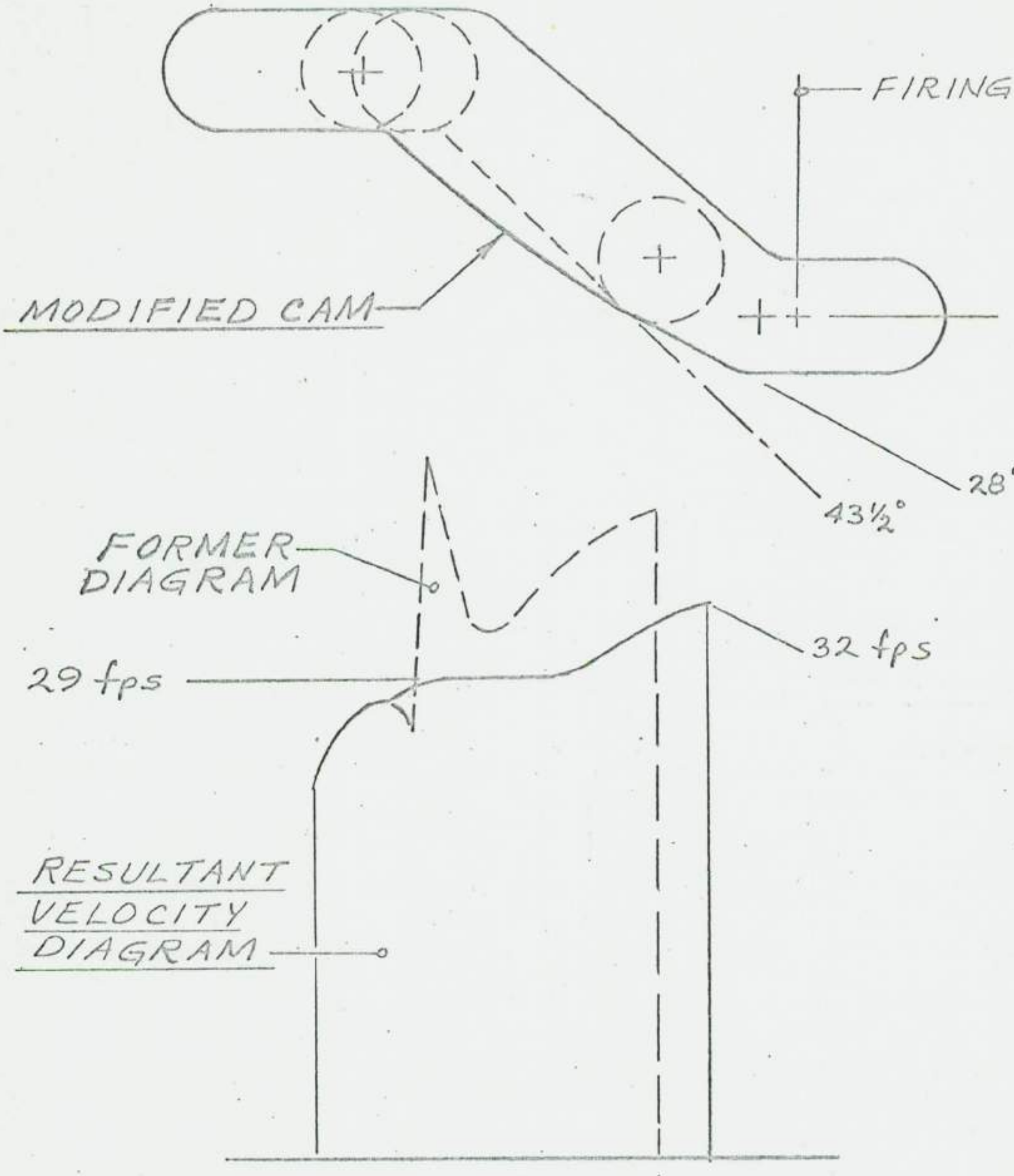
A time displacement diagram of actual feed slide motion during cocking was evaluated and the erratic velocity diagram indicates bouncing of the roller, and severe distortion of the feed slide arm. The peak velocity is in the order of 52-54 fps. The area under the curve is 6.81 in. , while in the previous diagram the area is 6.86 inches. This indicates that the total energy under each curve is similar; therefore confirming the mathematical process.

In a further study of this feed system, it is noted that the feed pawls engage the cartridge at a relatively high position on the periphery. The angle of loading to the cartridge center is 26°30', so that the load components $F_h = .89$ F and $F_v = .44F$ indicate a high vertical component tending to roll the cartridge.

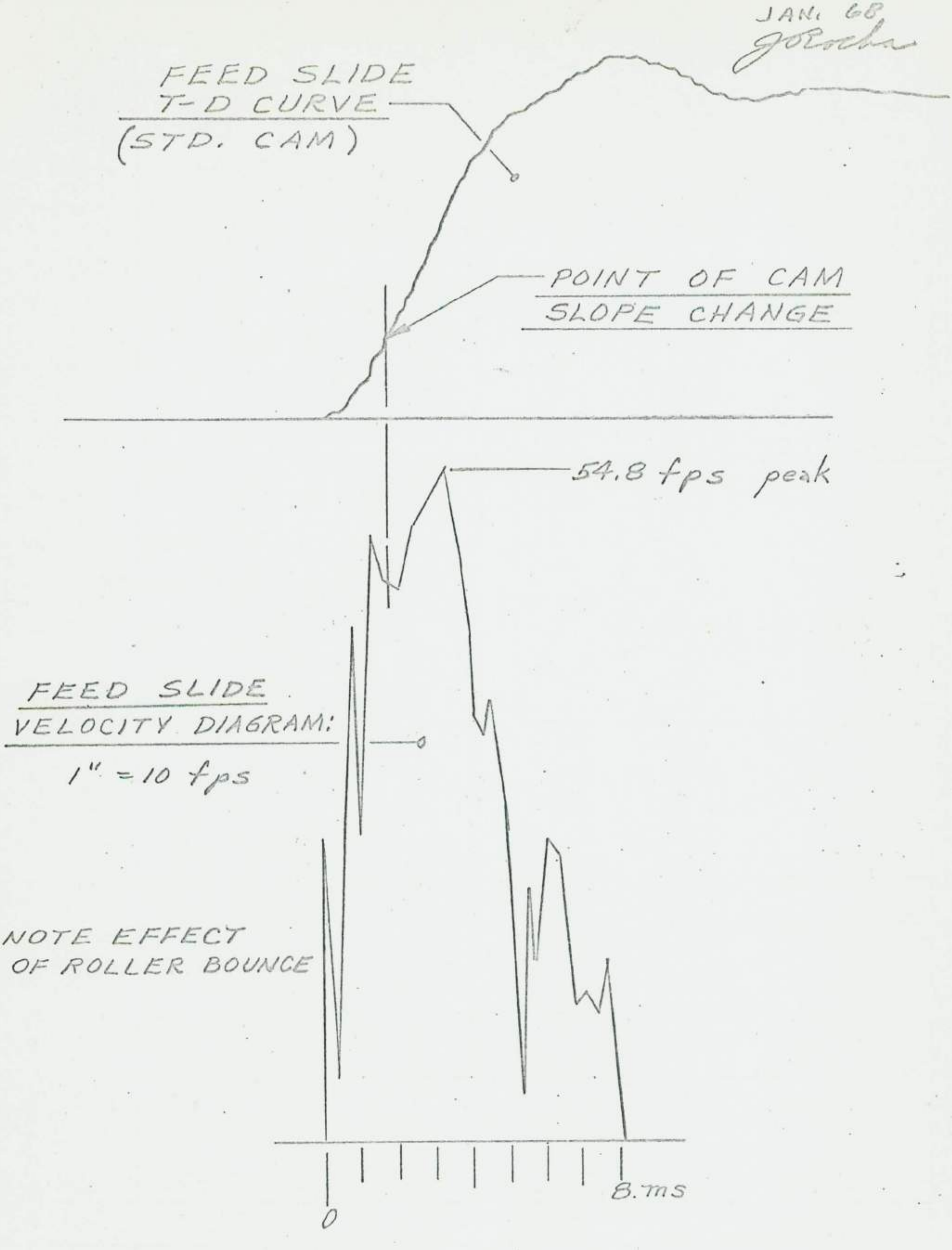


DERIVATION of FEED CAM LOAD DATA-"A"

JAN. 68
J. Rocha



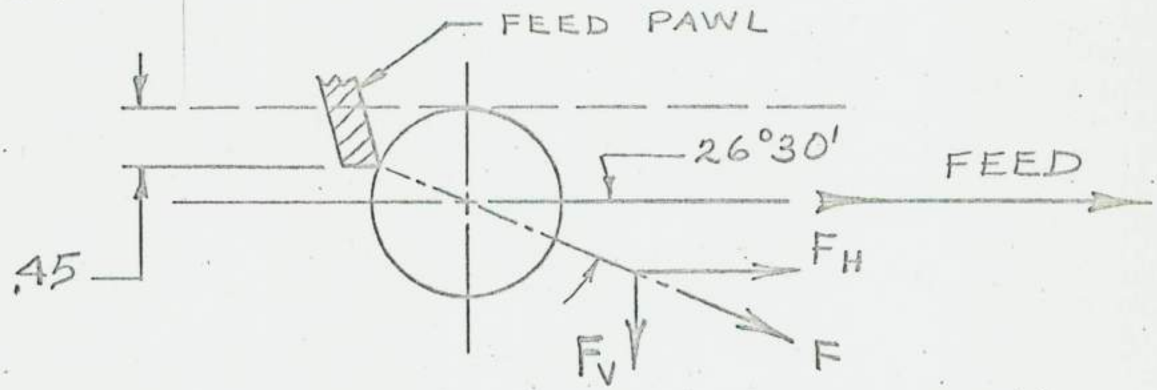
CAM MODIFICATION TO REDUCE INERTIA REACTION-FEED CAM "A"



FEED CAM LOAD DATA - "B"

The feed pawl should be pushing at a low point on the periphery. This will result in lower operating energies of the feed system, so that spring peak loads can be reduced, cocking loads modified to a more favorable level, and more normal feed forces realized.

The .45 inch engagement of feed pawl with cartridge should be increased to (.53 to .56) resulting in drive angles of 21° to 18°.



At the same time, the feed springs may be changed. This feed system is limited in belt pull by the load available at the end of the stroke. Therefore, the peak loads at the beginning of feeding may be reduced by using a spring of a lower rate.

In the present feeder, the springs have a load (at the end of the feed stroke) of 32 pounds, but in belt pull firing tests, can pull a load of only 13 pounds. This indicates an efficiency of only 40%, demanding the improvement in geometry noted above.

The following spring is recommended, compared with the present spring:

	Present	Recommended
Outside diameter	.575	.575
Wire diameter	.080	.070
Number of coils	43.	60.
Rate lb/in.	12.	4.5
Assembly load, lb.	16.	20.
Peak load, lb.	51.	33.

The bolt lugs should be re-designed to eliminate the high transverse load that is causing the bolt body to crack. The locking lug is an angled block that is positioned at an angle 18° to the horizontal. This causes a vertical component of force of 32% of the load to act in the direction that previous bolts have cracked.

The sharp inside rail corner should also be eliminated by a generous fillet. The sharp corner augments unnecessarily high stress concentrations.

The bolt cam plate should have both sides of the cam path parallel to each other, to prevent bolt lock bounce during function.

Further, the last round sensor should be removed. This is a device that holds the feed slide in a cocked position after the last round in the belt of ammunition is fired out. This device creates a safety hazard in that when one raises the cover, his fingers may well be in the slide path, and if the sensor is inadvertently touched, the slide is released with devastating results. This is very likely to occur during normal servicing. Functionally, the mechanism is not important.

Maximum recoil acceleration is shown as an 86° lift angle in the velocity diagram. This is equivalent to an acceleration of 42,000 fps^2.

Using $F = m a$, $F = 13.03 \times 42{,}000/g = 17{,}000$ lb. This agrees with a chamber pressure of 10,000 psi, which develops a load of 20,000 lb.

Duration of the acceleration peak is .41 ms.

Also, considering that theoretically, recoil velocity is inversely proportional to bullet mass, we have:

$W_w V_w = W_p V_p$
$V_p = 790$ fps
$W_p = .532$ lb.
$W_r = 13.03$ lb.
$V_r = .532 \times 790/13.03 = 32.3$ fps.

This should agree with the total turn-around velocity, which is 7.0 in counter-recoil and 25.48 in recoil, for a total of 32.48 fps.

Therefore observed results are in agreement with the general theory.

A further study of the critical feed slide / actuating mass reveals the following relationships:

a. With a feed slide of 1.1 lb., the reaction due to a 57,000 fps acceleration is $1.1 \times 57{,}000/g \times 1.95 =$ <u>3800 lb</u>. (from item 8.)

b. The comparable barrel force at the same point:

$W = 13.03$ lb.
$V_1 = 24.6$ fps
$V_2 = 23.0$ fps
$t = .3$ msec.
$\therefore\ a = 5320\ \text{fps}^2$
$\therefore\ F = m\,a = \underline{2160\ \text{lb.}}$

This is why the barrel mass does not have sufficient force to drive the feed slide efficiently, but rather causes a sharp loss of energy in the primary mass.

c. The energy absorbed by the feeder during the period of high acceleration:

$$E = \frac{W}{2\,g}\ (24.6^2 - 23.0^2) = \underline{15.8\ \text{ft.} - \text{lb.}}$$

Barrel stroke = .0079 ft. during this period

$F = 15.8/.0079 = \underline{2000\ \text{lb.}}$

d. Energy transfer from barrel mass to feed slide (per T-D curve)

$t = .00118$ sec. (note increase from theoretical .0003 time)

$$E_s = \frac{W}{2\,g}\ d\,V = \frac{1.1}{64.4}\qquad (53^2 - 45.3^2)$$

$E_s = \underline{13.\text{ft. lb.}}$

This agrees with the 15.8 ft.-lb. given up by the barrel.

e. An energy distribution chart was calculated for the eleven millisecond time period after firing. This is the critical portion of the cycle in which the area of inefficiency predominated:

Energy Distribution for 11 msec after firing:

t	Mass Energy	Diff	Slide Travel	Slide Energy	Spring Eg	Diff
1	45	+45.	-	-	-	-
2	123	+78.	0	2.45	-	+2.45
3	143	+20.	.35	26.	1.0	+24.5
4	98	-45.	.9	37.5	3.2	+13.7
5	62	-36.	1.55	46.0	6.3	+11.6
6	70	+8.	2.1	22.5	10.	-20.
7	81	+11.	2.44	9.8	12.5	-10.
8	88	+7.	2.62	3.3	13.8	-5.
9	94	+6.	2.8	.83	15.3	-1.
10	93	-1.	2.9	0	16.2	0
11	91	-2.	-			

Energy in ft. - lb.
Travel in inches

The most significant relationships are:

At ms (4), 31% of mass energy is transferred to feed system

At ms (5), 32% transferred to feed system

At ms (6), 40% of slide energy is transferred to mass (bolt & barrel)

Total energy released from mass to feed system = 49 ft. lb.

Total energy absorbed by feed springs = 16.2 ft. lb.

Efficiency = 33%

In conclusion; the weapon appears to be sensitive to the following combinations:

(a) Feed spring load vs. sear spring load,
(b) Drive spring load vs. sear plate spring load,
(c) Bolt bounce time at sear vs. time for feed pawls to engage round and start feed,
(d) Barrel unlocking time vs. time for cam plates to initiate bolt locking,
(e) Gouging between feed lever roller and bolt, causing sharp energy losses,
(f) Alignment of corner of link with cartridge stop rod.

These critical areas must be eliminated if the weapon is to be suitable for service.

18. Summarizing the recommendations offered:

(a.) Improve feed cocking cam contour
(b.) Feed pawls should be lowered
(c.) Feed springs should be changed to reduce peak load.
(d.) Use stranded wire for drive springs
(e.) Radius the corners of the feed arm roller
(f.) Improve bolt lock geometry
(g.) Hard-coat guideways in aluminum receiver. (In the long run, a steel receiver would be more favorable)
(h.) Remove last-round sensor
(i.) Relocate anti-surge pawl to a position nearer the bolt.
(j.) Finally, avoid sharp, re-entrant corners through the weapon design.

The Soviet AK-47 Assault Rifle

Brief History of Soviet Automatic Rifle Development

Prior to the Soviet activity in automatic rifle systems, the standard bolt action rifle was the 7.62mm 1891 Mosin-Nagant, in several rifle and carbine versions. Advances in automatic weapon development led to the 6.5mm 1916 Federov, the 7.62mm Simonov Automatic Rifle of 1936 and the 7.62mm Tokarev semi-automatic rifle of 1940. The Tokarev is quite similar in principle to the Belgian FN rifle.

These weapons did not prove to be suitable for service, so the bulk of infantry weapony in World War II featured the PPD and PPSh series of sub-machine guns chambered for the Type P-7.62mm Pistol Cartridge with a muzzle velocity of 1640 fps. Longer range firing required extensive use of heavy machine guns.

Accordingly, since the effective range of the sub-machine guns was limited, a family of weapons built around a more effective, but lightweight, cartridge was required. This led to the development of the 7.62mm M43 cartridge that apparently was a counter-part of the 7.92 German Kurz (short) cartridge. The effective range is in the order of 440 yards. Evidently, the trade-off between "firepower" as a matter of number of rounds carried and "firepower" as a matter of effective range, was well considered.

The submachine guns of World War II are no longer used in the Soviet armies, being replaced by the AK-47 types. A number of satellite armies still retain the sub-machine guns, of economic necessity.

As discussed previously, the following analysis is only visual, as instrumented firing records were not available.

Analysis of Soviet AK-47 Assault Rifle

The Soviet 7.62mm Model AK-47 is a magazine fed, percussion fired, gas operated, semi/full automatic weapon. In its geometry, it has a slight drop-stock, pistol grip, with the gas piston located above the barrel, ramp-type open sights, with a battle range setting of 300 meters, and a mid-height front sight.

The thirty-two round magazine curves forward, to suit the accumulated taper of 32 rounds, and extends approximately 7.0 inches below the receiver.

The selector lever also functions as a receiver dust cover when the selector is in the safe position. This provides good visual reference for the shooter as well as "touch" reference at night-time.

In general appearance, with a short barrel and pistol grip, it may be first considered as a sub-machine gun, but the 7.62mm cartridge places it nearer the rifle class.

Its principal characteristics, compared with the U.S. M14 rifle are as follows:

	AK 47	M 14
Overall length	34.5 in. (no flash supp.)	44 in. (with flash supp.)
Barrel length	16.37 in.	22.0 in.
Weight without magazine	8.4 lb.	8.2 lb.
Magazine weight	1.0 lb.	.5 lb.
Magazine capacity	32 rounds	20 rounds
Fire type	semi/full auto	semi auto (selector optional)
Bolt carrier dwell	.35 in.	.40 in.
Travel to end of unlock	.68 in.	.94 in.
Total bolt carrier travel	5.32 in.	
Bolt rotation to unlock	35°	

Ammunition Characterisitics:

	M43 (AK 47)	NATO (M 14)
Caliber	7.62mm	7.62mm
Round weight	253 grains	375 grains
Round length	2.18 in.	2.8 in.
Case length	1.52 in.	2.01 in.
Projectile weight	122 grains	150 grains

	M43 (AK 47)	NATO (M14)
Charge weight	25 grains	47 grains
Muzzle velocity	2329 fps	2800 fps
Effective range	440 yards	660 yards

There are five variations of the Soviet M43 cartridge (1) Ball type with mild steel core, (2) Tracer type T-45, (3) Armor piercing, incendiary, (4) Incendiary tracer, and (5) Blank, with rosette style crimp.

Additional AK-47 Technical Data:

Weight of reciprocating masses:

Bolt assembly	.198 lb.
Bolt carrier assembly	.99 lb.
Drive spring assembly (.066/2)	.033 lb.
Total	1.221 lb.
Ratio of primary mass to secondary mass	5.01/1

Firing Mechanism:

Firing pin weight	.0139 lb.
Hammer weight	.101 lb.
Mass Ratio	7.27/1.0

Gas System

Piston diameter	.548 in.
Piston travel before bleed	.70 in.

Gas regulator: none required

Rate of Fire Approx. 600 shots/min.

The breech mechanism consists of a rotating bolt actuated by a reciprocating bolt carrier. The bolt carrier rides in keyways in the receiver. An internal cam is machined in the forward section of the bolt carrier and rotates the bolt during the locking and unlocking phases of the cycle. Two locking lugs are positioned at the front of the bolt and are diametrically opposed. The lock cam lug is mounted on the outside periphery of one of the bolt lugs, increasing the moment arm for a favorable cam force leverage. This mechanism is a further development of the U.S. M1 rifle bolt mechanism. Note the highly favorable mass ratio between bolt carrier and bolt. (5/1)

A slender cylindrical section of the bolt body is supported in the bolt carrier. The bolt also contains a free-floating firing pin and an extremely simple cylindrical extractor.

A single drive spring, mounted in a telescoping guide rod, drives the bolt carrier assembly in counter-recoil. The guide rod base also functions as a cover latch; therefore the spring serves double duty. Also, when the spring assembly unit is removed, it remains as an easily handled sub-assembly. The receiver housing may be removed and the weapon function, for visual inspection of the operating mechanism, may be studied.

The gas system is of the plain impingement system, with the piston being an integral part of the bolt carrier. The piston end is concave, as is the end of the gas piston housing. This provides an initial chamber volume. The upper handguard is also the piston housing, with gas bleed holes incorporated in the gas cylinder extension. A single gas orifice is used, with no adjustment for power necessary. The gas piston is ribbed, for rigidity, and the operating rod is easily accessible for the bolt cam cuts.

The receiver also functions as the firing mechanism housing assembly. The firing mechanism is not a modular unit, as in the M1 rifle. The firing mechanism has eleven parts, including three retaining pins. The automatic sear spring has a single long arm that groove-locks these pins. Three sears are used in this mechanism with a double claw hammer for the primary and secondary sears, and a single (hammer hub) notch for the automatic sear, actuated by the operating rod. The primary and secondary sears are identical to the M1 in principle. When the hammer is in battery position, the safety can be applied. This would cause a jam when attempting to charge the weapon. However, the charging slot closure is a good visual indicator that the safety is on.

The selector shaft controls the functioning of the semi-automatic sear and trigger.

The front sight is a hooded post which can be adjusted by using the combination tool in the tool kit, either by screwing up or down, or moving left or right. The rear sight is of the conventional V-notch tangent leaf, the sight radius being approximately 15 inches. The upper forearm is retained by a latch on the rear sight. When the upper forearm is removed, a latch for the lower forearm is revealed. The lower forearm conceals a hiding pocket in the receiver.

The curved magazine tube is made of heavy gauge spot-welded construction with critical areas, such as the feed lips and catches, being machined. The magazine follower is a stamping, with a long skirt to control tipping, by its close fit with the inside wall of the magazine.

The magazine contains a number of highly desirable design features. The extremely rugged magazine lips are most favorable for extended field use. The magazine follower does not have to be critically balanced between ammunition stack and follower spring. No matter where one bears down on the follower (the center, forward, or rearward positions) the follower moves in the magazine tube smoothly. The spring design, therefore can be simple oval coils, free of stress concentrations, and free from binding along the magazine ribs.

The magazine follower design, together with the 5/1 mass ratio between bolt carrier/bolt are the two reasons why this weapon continues to fire in the field with old, corroded, apparently unusable, ammunition.

A hole at the lower rear surface of the magazine tube is an excellent visual indicator that the magazine is full. The user merely adds rounds to the magazine until the bottom round shows up in the hole.

A three piece tool kit is mounted in the buttstock, with a spring-biased pressure plate facilitating entry and removal. The kit contains a combination tool, a bore brush, and a cleaning patch prod, or jag. The combination tool provides a screw driver blade, a punch, and two wrenches. The cleaning rod is stored under the barrel and through the lower hand guard. The body of the tool kit is a tool handle, and the cap can be attached to the muzzle of the barrel as a guide for the cleaning rod, and, presumably, as a blank firing attachment.

The cycle of operation is quite identical, in principle, to the M 14 rifle, except that a fixed ejector, integral to the receiver, is used.

Weapon field stripping is accomplished without tools, by a system of guide slots in the receiver, for the operating rod, and retaining latches for the upper and lower hand guards.

The barrel is rifled with 4 lands and grooves, with a right hand twist. The muzzle attachment nut is threaded left-hand. The gas port is at an angle, which simplifies cleaning. No parts other than the gas piston and upper forearm are removed for this bit of maintenance. Training in weapon maintenance is considered to be fairly simple. While not convenient for bayonet fighting, the short weapon length is handy for street and house-to-house fighting. The basic weapon is also equipped with a folding buttstock, for paratroop and special services.

Note that no flash suppressor is used, in spite of the short (16.3 in.) barrel; however the powder charge is low, being only 25 grains.

An estimate of production cost was made, and based on a quantity of a lot of 2 million rifles, the weapon would cost approximately $60.00 without product engineering or final inspection services. Also, it was estimated that approximately 550 machine operations are necessary, as against 800 for the M14 rifle. The weapon is almost completely made from milled steel components, with few stampings being made. This is a reversal of form, since most World War II Soviet weapons used stampings en masse. The receiver has relatively few complex milling cuts, and an insert is used to cam the bolt into the barrel extension at the start of the locking rotation.

This weapon is standard issue not only in the Soviet Union, but also in the satellite countries of East Germany, Rumania, Hungary (with modified handguard and plastic pistol grips) as well as in Communist China, which designates their production as 7.62mm type 56 assault rifle. This is supplied to North Vietnam also. The Czech assault rifle is similar in outward appearance, but is redesigned internally to a different mechanism.

In summary, the AK-47 weapon employs a compact, essentially well-designed bolt mechanism, with the action suited to the short 7.62mm cartridge. Generally, this cartridge is considered in Europe as the "mid-'30" cartridge, that is, of energy levels mid-way between the U.S. Cal. .30 carbine and cal. .30'06 cartridges. It is considered as a further development of the German 7.92 mm Kurz (short) cartridge. However, for machine guns, the Soviets still retain their old 7.62mm rimmed full length cartridge (as well as in accuracy match rifles).

AK-47 accuracy is nearer rifle class than sub-machine gun class, as should be expected. The average submachine gun firing single shots will produce a group of from 12 to 18 inches diameter at 100 yards. The AK 47 will group in 6 inches at 100 yards. In full automatic fire, the weapon climbs rapidly, when firing bursts of 5 or more rounds, therefore a good gripping position on the forestock and sling is necessary.

The weapon fires from the closed bolt position for either the semi automatic or full automatic cycles of operation. There is no bolt-hold-open device to hold the action open after the last round in the magazine is fired.

The AK-47 will eventually be replaced by the AKM, a modification which is characterized principally by a sheet metal receiver, rather than the milled receiver, as well as several other minor changes.

VII Bibliography and Recommended Reading

Much of the material discussed in this manuscript is taken from data developed at Springfield Armory. All of the material is unclassified.

Many of the chapters are augmented by supporting data taken from several Ordnance libraries. A bibliography lists the books used, together with an identifying subscript which correlates the sources with the corresponding chapters of the manuscript.

For additional data, on any of the topics listed, the volumes noted should be used for reference, among others.

The designation "SA" indicates topics in which Springfield Armory data was prominent. Certain chapters, notably on "Firing Mechanism Design" and "Feeding" contain only SA data. Much of this has not been documented previously, and is knowledge acquired through "on-the-job-training" at Springfield Armory.

BIBLIOGRAPHY

Reference		Author
a	"Small Arms of the World"	Smith & Smith
b	"Hatcher's Notebook"	J. S. Hatcher
c	"The Machine Gun" (4 Vol.)	G. M. Chinn
d	"Treasury of the Gun"	H. L. Peterson
e.	"Oerlikon Pocket Book"	Oerlikon Works
f	"Principles of Firearms"	C. E. Balleisen
g	"Elements of Ordnance"	Hayes
h	Winchester Ammunition Handbook	O M C C
j	"Ballistics"	Cummings
k	"Cartridges of the World"	F.C. Barnes
l	"Ordnance"	published bi-monthly
m	"The Bullet's Flight from Powder to Target"	F. W. Mann
n	"The Gun and its Development"	W. W. Greener
p	"World War I"	S. L. A. Marshall
q	"Handbook of Mech Spring Design"	Associated Spring Corp
r	"Spring Design & Application"	N. Chironis
s	"Cams"	H. A. Rothbart
t	"Formulas for Stress & Strain"	R. J. Roark
u	Speer Reloading Manual #7	Speer, Inc.
v	NRA Fact Book (Firearms & Ammo)	NRA
w	"Gun Digest"	published annually
x	"Shooter's Bible"	published annually

Bibliographical Reference	TOPIC IN ORDER OF CONTENT
	1. Introduction
	2. Historical
d,e,n,v	Development of the Military Cartridge Case
SA,a	U.S. Light Rifle Program
SA, 1	Caseless and Liquid Propellant Systems
	3. Supporting Sciences
SA,b,c,e,f,k,m,u,v	Interior Ballistics
SA,b,e,h,u	Exterior Ballistics
SA,b,e,g,v,w	Recoil
SA,1,(Jan 1964)	Dynamics of Automatic Rifles
	4. Systems of Operation
SA,f,c	Blowback
SA,e	Recoil Operation
SA,e	Gas Operation and Analysis
	5. Weapon Design
SA,b,v	Headspace
SA	Factors of Safety
SA,t	Barrel and Bolt Lug Stresses
SA	Firing Mechanism Design
SA	Feeding
SA,c	Link Design
SA	Magazine Design
SA,q,r	Spring Desing
j,p,b,f,v	Muzzle Devices
	6. Weapon Analysis
SA,c	Time - Displacement Curves
SA,s,t	Analysis of recoil-operated machine gun
a,1	Analysis of Soviet AK-47
	7. Bibliography & Recommended Reading
	8. Courses of Study

SA designates "Springfield Armory"

VIII Courses of Study

In becoming knowledgeable as to Small Arms Ordnance principles and practice, there are a number of sources of information available to the design engineer. These include the following:

a. Hardware and Literature Survey

b. On-the-job training

c. Extension courses

The "hardware and literature survey" includes both museum and library facilities and will familiarize the engineer with many of the facets of ordnance engineering conducted in the past. Much engineering has been done in the past that was not successfully concluded because of production limitations, metallurgical limitations, and other requirements that would not pose a barrier today. The physical principles employed are the important elements, rather than the outward appearance.

On-the-job-training is highly specialized and time-consuming training process. The more knowlegeable an engineer is about prior art, the less likely he is vulnerable to making a false start. However, he should not be limited to prior art, as quite often a bold new approach will result in marked improvements in performance. Proper supervision in "on-the-job-training" stabilizes the engineer and the program.

Extension courses are most valuable in augmenting both prior art studies and on-the-job-training. These are available to engineering personnel and usually are free of charge. The Ordnance School conducts a wide variety of these courses; the ones of principle interest are as follows:

	Credit Hours
ORD 4 - Fundamentals of Ballistics	16
ORD 411 (61) Machine Guns	19
ORD 413 (63) Hand & Shoulder Weapons	14
ORD 508 (111) Research & Development	10
ORD 601 Weapons Familiarization	5
ORD 605 (60) Principles of Small Arms	13
ORD 606 (69) Armament Principles	12
ORD 713 Aircraft Armament Subsystems	2

Personnel may apply for these, and other, courses by filing a DA Form #145, and in block #7 address:

Commanding Officer
Rock Island Arsenal
Rock Island, Illinois 61201
ATTN: SWERI-PTT-2430

or through the training branch of any other appropriate installation.

Other courses of interest include those in an engineering curriculum such as: Strength of Materials, Kinematics, Dynamics, Metallurgy, etc. with "Strength of Materials" considered as the most important one by this writer.