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INVESTIGATION OF DRIVE POWER REQUIREMENTS IN HIGH RATE OPEN CHAMBER WEAPONS

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Technical Report AFATL-TR-68-51

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AIR FORCE ARMAMENT LABORATORY
AIR FORCE SYSTEMS COMMAND
EGLIN AIR FORCE BASE, FLORIDA

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FOREWORD

This report was prepared by TRW Systems Group under United States Air Force Contract No. F08635-68-C-0005. The work was administered under the direction of the Air Force Armament Laboratory with Mr. A. Travis Cox (ATWG) as program monitor.

Information in this report is embargoed under the Department of State International Traffic in Arms Regulations. This report may be released to foreign governments by departments or agencies of the United States Government subject to approval of the Air Force Armament Laboratory (ATWG), Eglin AFB, Florida 32542, or higher authority within the Department of the Air Force. Private individuals or firms require a Department of State export license. This report contains no classified information extracted from other classified documents.

This technical report has been reviewed and is approved.

Charles [illegible]
/ George P. Brenner, Colonel, USAF
FO Chief, Weapons Division

ABSTRACT

The use of high rate-of-fire open chamber guns could be limited if power required to drive them proves excessive. Drive power is proportional to the gun and cartridge geometry, $(\text{rate of fire})^2$, and sliding friction between the cartridge cases and the frame members forming the non-rotating parts of the firing chamber. "Handbook" values for friction coefficient do not apply since the bearing pressures and sliding speeds range far in excess of available data for materials of interest. The effects of dissipated heat are also shown to be highly significant since the plastic cartridge cases have a relatively low melting point. An eight-barreled test fixture was designed and built to simulate the conditions of a small open chamber gun firing at rates up to 600 shots/sec. Test ammunition was developed in both percussion and electric-primed versions. Twenty-nine firing tests were made to measure sliding friction while varying rate of fire, frame material, cartridge surface coatings, and number of shots fired. At sliding speeds representing low rates of fire, friction coefficients were comparable to handbook values, that is ~0.16, but above a critical speed the coefficients dropped into the range 0.02-0.04, verifying the occurrence of melting at the cartridge case surface. A dry film lubricant and a low temperature gasing coating were found ineffective in reducing friction. Friction coefficients in the range 0.02-0.04 can be expected for sliding speeds/normal forces high enough to promote melting of the cartridge case surface.

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SECTION I

INTRODUCTION

1.1 THE OPEN CHAMBER PRINCIPLE

The open chamber gun system is illustrated schematically in Figure 1. The plastic-cased cartridges of nominally triangular section are introduced laterally into corresponding recesses in the periphery of a rotating cylinder and carried under a fixed frame member (firing strap) which closes the chamber and supports the cartridge during firing. Further rotation of the cylinder ejects the spent case.

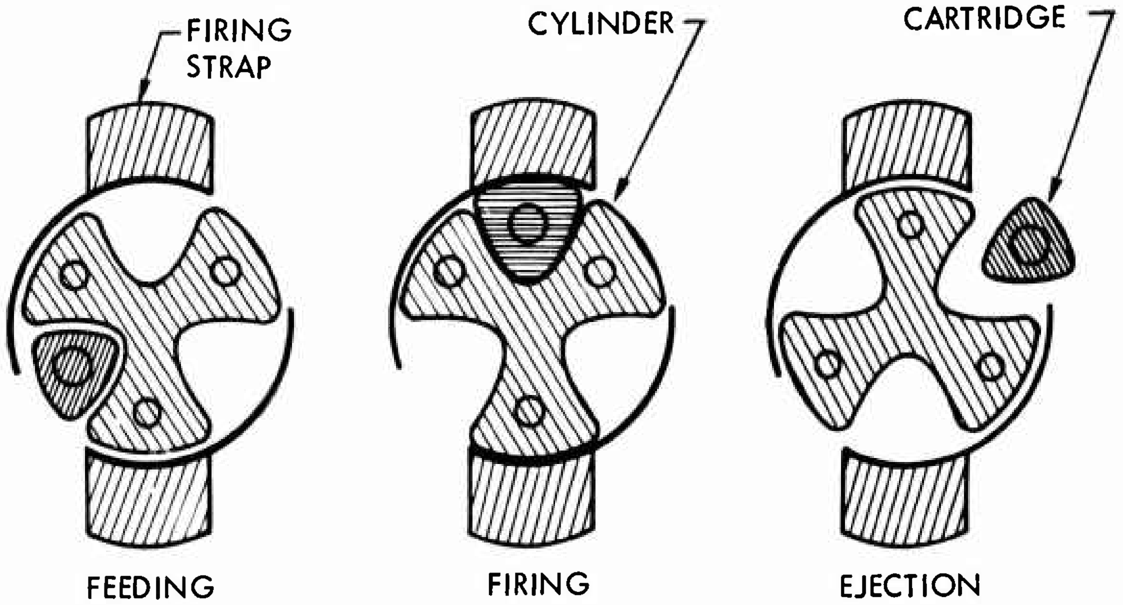

Figure 1. Operating Cycle of Open Chamber Gun

The simple cycle resulting from elimination of the reciprocating motions common to conventional guns permits rates of fire theoretically limited only by the duration of the pressure transient during firing and the width of the firing strap. However, it must be realized that the cartridge case slides across the firing strap while pressurized and dissipates energy as heat through friction in the manner of a conventional shoe in a drum brake. Thus, power must be applied to overcome friction and turn the cylinder to maintain the rate of fire.

1.2 FRICTIONAL DRAG ANALYSIS

During a shot, instantaneous drag force D in pounds is expressed by:

$$D = PA\mu \tag{1}$$

where

P = chamber pressure, lb/in^2

A = cartridge side area, in^2

μ = coefficient of sliding friction of case on strap

Work W done per second to overcome drag is therefore

$$W = \mu nVA \int_0^t P \, dt \tag{2}$$

where

n = rate of fire, sec^{-1}

V = sliding velocity, ft/sec

t = time case is pressurized, sec

V is proportional to n for a given configuration. Thus, if μ is independent of time, Equation (2) reduces to

$$W = Kn^2\mu \tag{3}$$

1.3 EFFECT OF FIRING STRAP CONTOUR

The preceding analysis applies if the firing strap contour conforms to that of the firing cylinder. Suppose instead that the trailing side is scarfed by a small angle θ as shown in Figure 2.

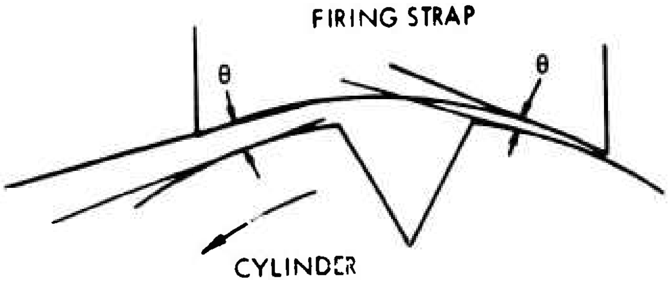

Figure 2. Scarfing of Firing Strap

In this case, a force component opposite to drag is created. If the scarf angle (in radians) is equal to the coefficient of friction, the opposing forces will balance. Of course, scarfing is limited by the ability of the pressurized cartridge case to bridge the gap thus created. For this reason, scarfing would be most effective when friction coefficients are relatively low, for the lower sliding speeds, and in combination with the stronger cartridge case materials.

1.4 EFFECT OF CARTRIDGE CASE AND FIRING STRAP HEATING

Because thermal conductivity of plastic cartridge cases is relatively low compared to that of the metallic firing strap, most of the frictional heat generated at the interface will initially go into strap. Ultimately, the temperature reached should be sufficient to cause surface melting of the case upon contact at which time the friction coefficient will presumably be reduced because of the liquid interface.

1.5 NEED FOR EXPERIMENTAL VERIFICATION OF FRICTION COEFFICIENT

It is necessary to know the coefficient of sliding friction (μ) between the cartridge case and firing strap in order to compute power required to drive a given gun at a given rate. Typically, handbook values for μ are based on measurements taken at pressures of a few hundred pounds per square inch and sliding speeds up to a few inches per second. These pressures and speeds are roughly two orders of magnitude lower than those present in high rate open chamber guns and therefore fail to induce any significant heating effect. Furthermore, the chamber pressure far exceeds the bearing strength of the plastic cartridge case materials, which could have a significant effect.

1.6 SCOPE OF EXPERIMENTAL INVESTIGATION

The contractor had under study a high rate open chamber weapon (HIVAP) with the planned characteristics given in Table 1. Figure 3 is a general illustration of the small caliber flechette-firing machine gun, and Figure 4 shows a cross section of such a mechanism. Figure 5 shows computed drive horsepower for this weapon for a range of μ values. A detailed analysis of frictional heating was performed for this design and is presented in Appendix I.

An open chamber single shot firing fixture had been used by the contractor to conduct a few experimental firings using machined triangular cartridge cases. The experimental program described herein was initiated to design and fabricate ammunition, to design and build a rotating fixture simulating the HIVAP weapon, (less feed mechanism) and to measure the friction over a range of firing rates and other variables.

TABLE I. PLANNED CHARACTERISTICS OF HIVAP OPEN CHAMBER WEAPON

GUN	
Rate of fire	variable to 600 shots/sec
Bore diameter/length	0.31 in./30 in.
Number of barrels/chambers	8
Number of feeds/firing stations	2
Diameter of firing cylinder	3.4 in.
Rotational rate at maximum rate	2250 rev/min
Power source	D. C. electric motor
AMMUNITION	
Muzzle speed	4800 ft/sec
Projectile weight	50 grains
Peak chamber pressure	50,000 lb/in^2
Cartridge length	3.1 in.
Cartridge side area	2.1 in.

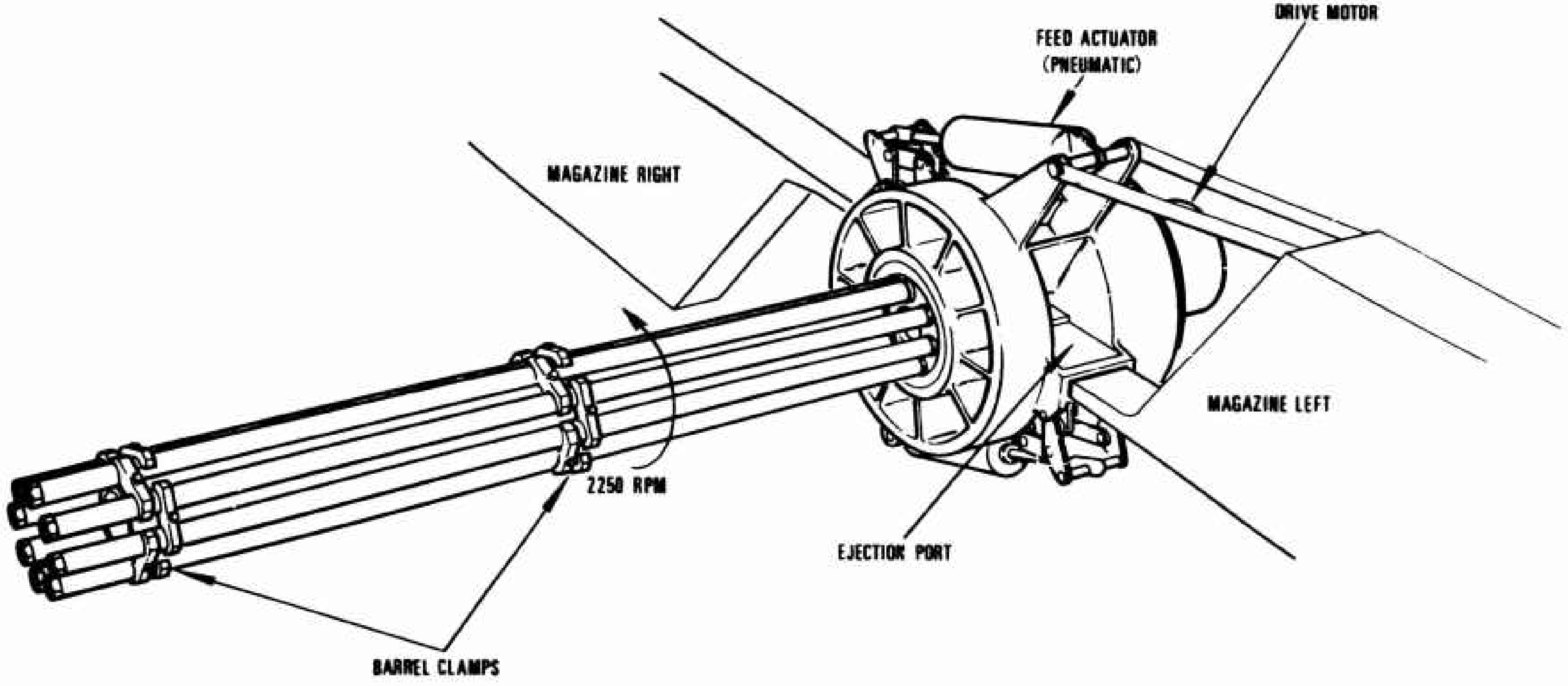

Figure 3. HIVAP Open Chamber Machine Gun

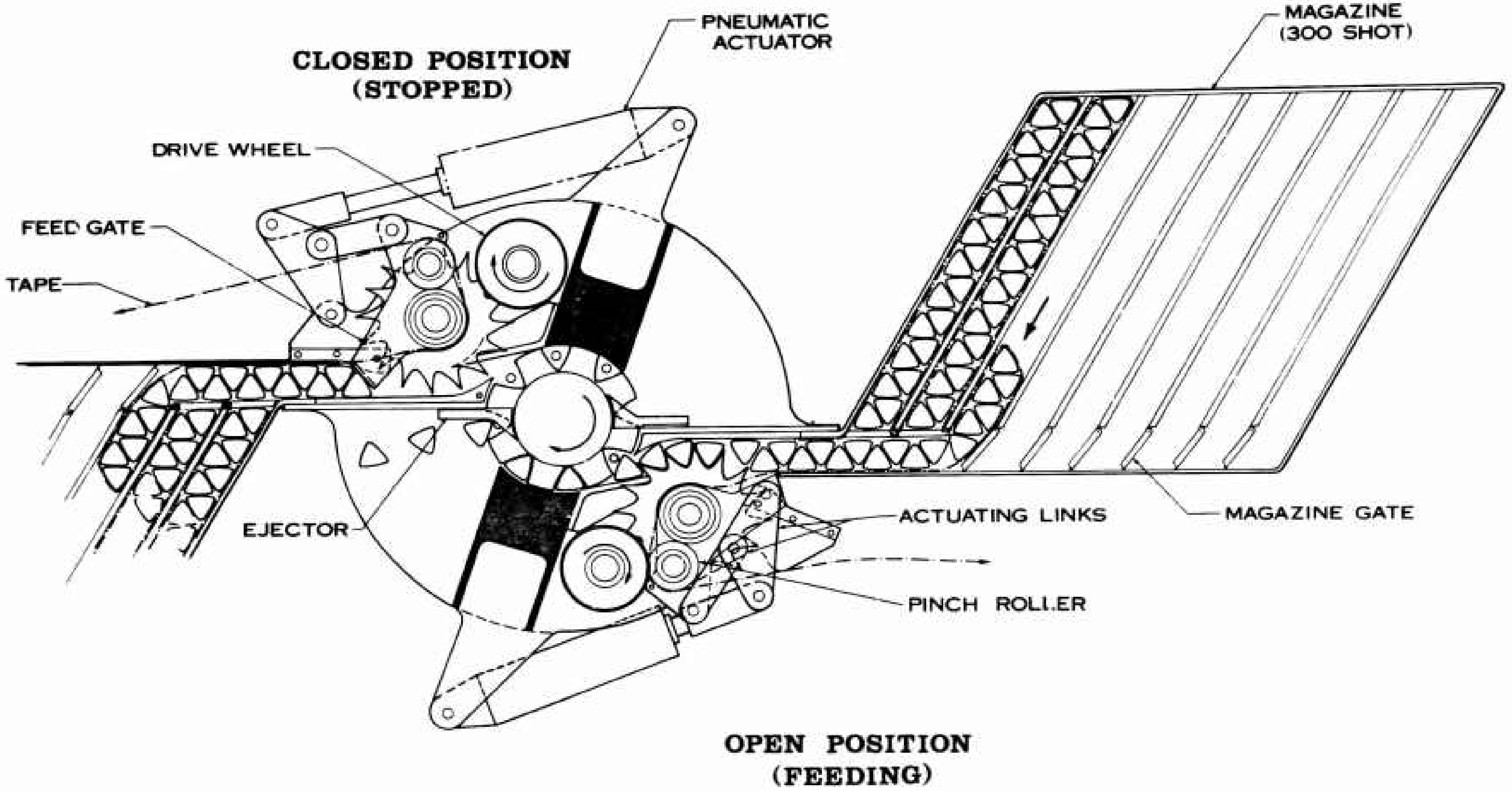

Figure 4. Cross Section of HIVAP Gun Mechanism

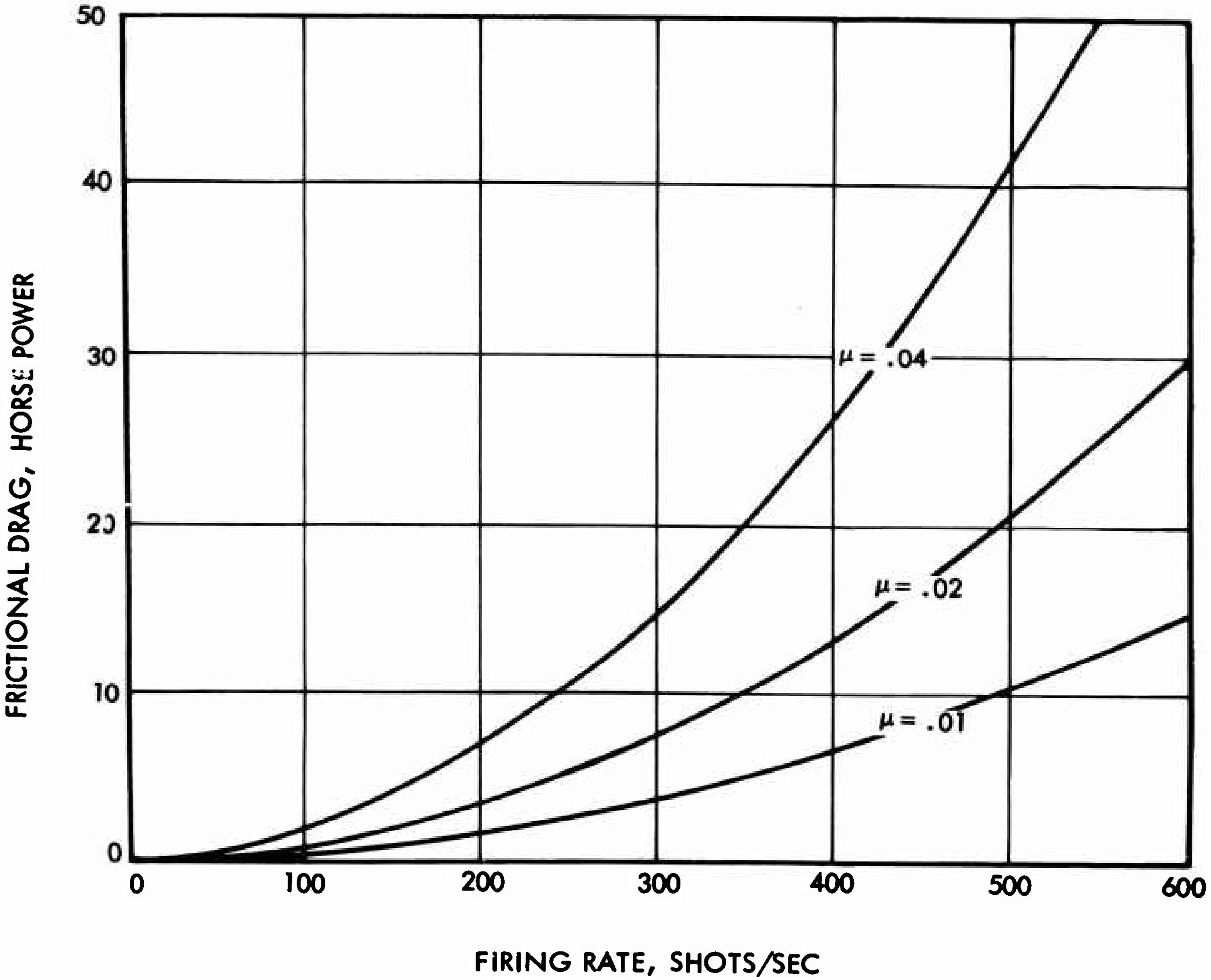

Figure 5. Frictional Drag in HIVAP Gun

SECTION II

AMMUNITION DEVELOPMENT

2.1 CARTRIDGE CASE DEVELOPMENT

The design of the ammunition is shown in Figure 6. It consists of a cartridge case body, an insert sleeve, a projectile consisting of a nylon sabot containing a steel rivet, magnum "large rifle" primer, and propellant.

Figure 6. Cross Section of Original Cartridge Design

2.1.1 Cartridge Case Materials and Molding

Based on stress analyses and the limited amount of data available concerning high rate impact loading on plastics, the materials listed in Table II were selected as candidates.

TABLE II. CANDIDATE CARTRIDGE CASE MATERIALS

Designation	Base material	Filler (if any)
F60-180	Linear polyethylene	None
Delrin 500	Acetyl resin	None
Ethofil G90/20	Linear polyethylene	20% Fiberglass
Profil G60/20	Polypropylene	20% Fiberglass
Nylafil G3/30 Type 6	Nylon	20% Fiberglass
Polycarbafil G50/20	Polycarbonate	20% Fiberglass

Cases were molded from the materials listed. During molding, the long core for the case body cavity was bending, resulting in cases with one thin wall and two thick walls. The mold was redesigned to give proper support to the core. Despite the presence of bubbles in the rear of the body for some of the higher viscosity resins (Polycarbafil, Nylafil), the cases were considered usable for interior ballistic testing.

Test firings were begun, using the candidate materials. The cases began to crack and break up at only moderate chamber pressures. None of the original six candidate materials gave indications of being able to perform satisfactorily, either because of low allowable elongations (glass-filled materials), or low strength (linear polyethylene). An attempt was made to mold some Lexan polycarbonate (unfilled) cases. The as-molded cases experienced rather severe bubble formation at the rear end (primer area). The thin-walled sections were less severely cracked during firing than with any of the original six candidates. Since Lexan showed the greatest promise, it was discussed in detail with the molding consultant and vendor. The existing molds were apparently unsatisfactory for the molding of Lexan and other high viscosity materials. They were, however, satisfactory for linear polyethylene (the prime initial candidate which performed poorly when tested). The molds were gated at the forward end of the case to provide uniform thin-wall sections. However, when using Lexan, a high viscosity and melting point material, molding pressure was not available to preclude bubble formation at the rear end of the case.

Although bubble formation continued, new cases were molded from Lexan for use in the friction tests.

2.1.2 Insert Sleeve Problems

Another type of failure in addition to case breakup was also evident in the firings. These were failures where the insert sleeve fractured or was eroded by gases and at times followed the projectile down the barrel. The cartridge case design required the propellant gas pressure to press the tip of the sleeve against the case wall to provide a passive seal at the same time the sleeve moved forward to seal at the barrel face. In some instances, an obvious air space was visible, and on a few fired cases where the insert remained intact, the results of erosion were clearly visible between the case and sleeve.

Since the sliding sleeve approach did not appear promising, it was decided to bond the sleeve to the case body and allow the entire case to elongate to provide obturation at the barrel face. A number of sealants were tried, the best being a solvent bond of the two parts using methylene chloride. When fired, the cartridges stretched to seal against the barrel face without breaking the bond.

2.1.3 Primer Leakage

The first design of the case was intended to have the primers pressed directly into the plastic case (Figure 7). The first tests indicated that the primers would require more containment. Some of the types of primer cups that were subsequently tried are shown in Figure 7. Eventually, the fourth design was selected. The case mold was then modified to mold-in the cavity for the brass primer holder. In addition to eliminating machining, a desirable side effect occurred. Bubbles in the base area occurring during the molding of the early cases frequently caused case cracks and leakage during firing if they extended into the powder cavity. With the thinner wall, the bubbles were much smaller and isolated.

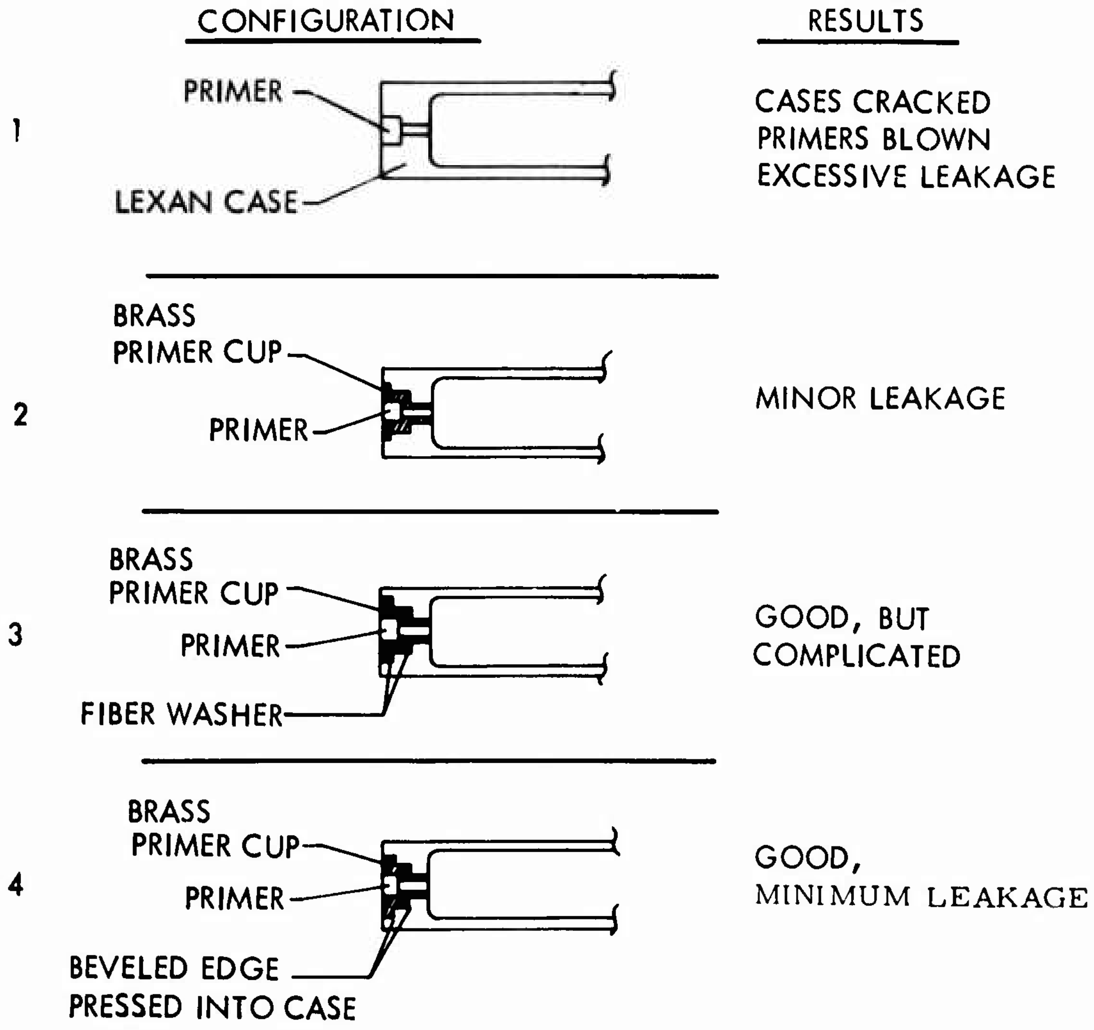

Figure 7. Primer Configurations Investigated

2.1.4 Case Material Additives

Studies performed indicated that small percentages of certain additives may be introduced into the basic Lexan polycarbonate to increase toughness and eliminate the random cracking which sometimes occurs. Test bars were made using 1% polyurethene additive, and the results were very encouraging; that is, improved elongation with no loss in tensile strength. However, actual cases utilizing the additives could not be molded in time to test on this program.

2.2 INTERIOR BALLISTICS DEVELOPMENT

This phase of the program was to establish the interior ballistics of the ammunition; for example, charge weight, peak chamber pressure, and muzzle velocity.

2.2.1 M-9 Testing

Based on an interior ballistics computer study, M-9 propellant was selected as a prime candidate propellant, and initial tests employed it. At lower chamber pressures (below 20,000 psi), the propellant performed as predicted. However, as the charge was increased and higher pressures were encountered (greater than 20,000 psi), the case began to break up (except for linear polythylene, which extruded). At this point, it was evident that although M-9 could be used in conventional brass case ammunition, it was too "hot" for the present usage; that is, peak pressure and associated impact loading were too great with respect to the resulting muzzle velocity.

2.2.2 Alternate Propellants

At this point, it was decided to use some of the propellants that were available in a greater variety of grain sizes than the M-9.

2.2.2.1 Ball Powder

A series of tests were conducted to optimize a mix of ball powder that would later be blended into a single formulation by Olin. Olin WC 660 (a fast formulation) and Olin WC 680 (a slower formulation) were employed. The first series of tests was run with WC 680, with results given in Table III. In general, difficulties were experienced in poor ignition, reproducibility, case failures, and especially muzzle flash. The muzzle flash ranged from relatively small fire balls approximately 1 ft in diameter to some that were 2 ft in diameter and 4-ft long.

TABLE III. WC 680 BALL POWDER PERFORMANCE

Charge, grains	P_{max}, 10^3 lb/in^2	Velocity, ft/sec	Comments
50	30	4100	Flash
60	44	4560	Flash
60	38	3785	Flash, cracked case
60	40	4435	Flash, cracked case
60	37	4365	Flash
60	29	3905	Case cracked
60	37	4335	Flash, cracked case
65	47	4660	Flash
65	46	4625	Flash
65	47	4800	Flash
65	43	4700	Flash

The next series of tests were run using WC 660, the fastest burning formulation. Results are listed in Table IV.

TABLE IV. WC 660 BALL POWDER PERFORMANCE

Charge, grains	P_{max}, 10^3 lb/in^2	Velocity, ft/sec	Comments
40	32	3200	
40	32	2840	
55	44	4750	Cracked case
55	48	4730	Cracked case
55	48	4520	Cracked case

At 60 grains, all cases were severely cracked, and peak pressures were exceeding 50,000 psi. In general, WC 660 was too "hot," giving excessive peak pressures for the muzzle velocities achieved and resulting in severely cracked cases.

Mixes of the two formulations were then tried; for example, 60/40 WC 660/WC 680, 50/50 WC 660/WC 680, and so forth. No mix was found that gave satisfactory performance.

2.2.2.2 IMR Propellant

Although considered an "old" propellant by some, IMR was selected because of its demonstrated capabilities, military acceptance, wide variety of formulations, and generally longer pressure/time burning characteristics (lower peak pressures with complete burning). A series of charge sizing tests were run using DuPont IMR 4227. When a confirmatory series of tests were run at the selected charge weight of 60 grains, the results were as shown in Table V.

Although a few cases cracked, the muzzle velocities were relatively consistent. No ignition difficulties or muzzle flash were encountered. To proceed with the friction test fixture firings, a charge of 60 grains IMR 4227 was selected as the baseline design.

2.3 GAP TESTS

To indicate the potential of applying "scarfing" to the top straps to reduce the horsepower requirements, a series of tests were conducted to determine the maximum gap, between the top strap and cylinder, which the cartridge case would be capable of spanning during firing without failures. The gaps shown in Table VI are those preset into the single shot firing test fixture. During firing, the gaps increase approximately 0.005 in. because of elastic stretch of the firing test fixture members. For the presently molded Lexan cases, 0.006 present gap (0.011 dynamic) appears to be the maximum allowable.

An interesting phenomenon appeared to have occurred during these tests: the peak pressures were reduced to below the normal for 60 grains of IMR 4227. A possible explanation is that the tests are deforming the cases past their yield point to fill the chamber, and this is occurring above a certain threshold and thereby reducing the peak pressure; that is, a constant volume system changes into a constant pressure system above a certain level.

TABLE V. IMR 4227 POWDER PERFORMANCE

Shot	P_{max} 10^3 lb/in^2	Velocity, ft/sec	Comments
1	35	3995	Case cracked
2	44	4485	
3	45	4635	
4	41	4615	
5	41	4615	
6	44	4615	
7	31	4235	Case cracked
8	42	4615	
9	40	4595	
10	38	4515	
11	40	4595	
12	39	4675	
13	31	4395	Case cracked
14	39	4515	
15	35	4665	
16	38	4555	
17	36	4585	
18	35	4665	

TABLE VI. GAP TESTS

Shot No.	P_{max}, 10^3 lb/in^2	Velocity, ft/sec	Gap, in. (Preset)	Case Condition
309	---	4605	0.002	OK
310	35	4595	0.002	OK
311	38	4675	0.002	OK
315	38	4515	0.006	OK
316	35	4375	0.006	OK
317	33	4415	0.006	OK
312	35	4485	0.012	OK
313	35	4735	0.012	OK
314	28	4215	0.012	Split
318	26	3965	0.013	Split
319	34	4335	0.013	Split
320	33	4365	0.013	Split

2.4 ELECTRIC PRIMER DEVELOPMENT

One thousand off-loaded M52A3B1 primers were received from Lake City Arsenal. The arsenal also provided a copy of a letter[1] to Air Force Armament Laboratory providing charge weight, sensitivity, and resistance data on the lot as produced. These are compared to the standard M52A3B1 in Table VII. Firing tests were conducted in the single shot test fixture with both bare and brass-cupped electric primers. The case leaked severely around the bare primer, but the cupped primers demonstrated improved sealing. Peak pressure and velocities using the 60-grain charge were both higher than with the same charge and percussion primers. The charge was reduced to 57 grains for comparable performance.

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[1] Letter 631-03390-93 from Department of the Army to Air Force Armament Laboratory, dated 15 February 1968, "Modified Electric Primers — Contract F08635-68-C-005, TRW."

TABLE VII. COMPARISON OF M52A3B1 PRIMERS

	Off-loaded	Standard
Charge weight, grains	1.35 ± 0.10	2.25
Sensitivity (all fire voltage)	274	160
Resistance, ohms	10,000-20,000,000	1000-1,200,000

SECTION III

FRICTION TEST FIXTURE DEVELOPMENT

3.1 DESIGN FEATURES

The fixture was designed to simulate essentials of the HIVAP weapon less its feed and drive components. In addition, the following features were provided:

- Reversing the usual arrangement, the barrels and cylinder are stationary, and the frame rotates. This has the advantage of simplifying the barrel retention and firing mechanisms and eliminating need for a thrust bearing.
- Acceleration to firing speed is provided by an electric motor turning a small pneumatic tire riding the frame periphery. A manual lever system engages and disengages this drive.
- The firing strap surfaces are separate inserts bolted to the frame so that different materials and clearances can be accommodated.
- The firing mechanism can be arranged to fire all eight shots under a single strap in sequence, or alternately four pairs of shots.
- Both conventional percussion and electric ignition systems are provided, the latter compatible with off-loaded M52A3B1 primers.

3.2 FIRING FIXTURE DESCRIPTION

The firing fixture as originally constructed for percussion ignition is shown in Figures 8 and 9. The cylinder and barrels are fixed to the mounting plate, and the frame rotates clockwise (viewed from rear). Radial loads of firing are reacted by two large roller bearings, one at either end of the cylinder. Thrust is taken directly into the mount. The firing mechanism arrangement can be seen in Figure 10. The firing pins are manually cocked by pulling them to the rear against spring tension and turning one-fourth turn. In this position the safety, consisting of a plate with slots for the cocking pieces, can slide forward to prevent rotation of the pins. An auxillary wedge is provided to lock the safety in either the on or off positions. Release of the firing pins is achieved by actuating one or both solenoids attached to the rear of the mount, depending on the mode of fire (one at a time or pairs) desired. The solenoid shafts, when forward, are contacted by the trip levers on the frame as they rotate past the solenoid position. The levers are cammed through approximately 90° and then slide forward 1/8 in. into a recess under spring action. In this position, the tip of the lever contacts the firing pin cocking pieces

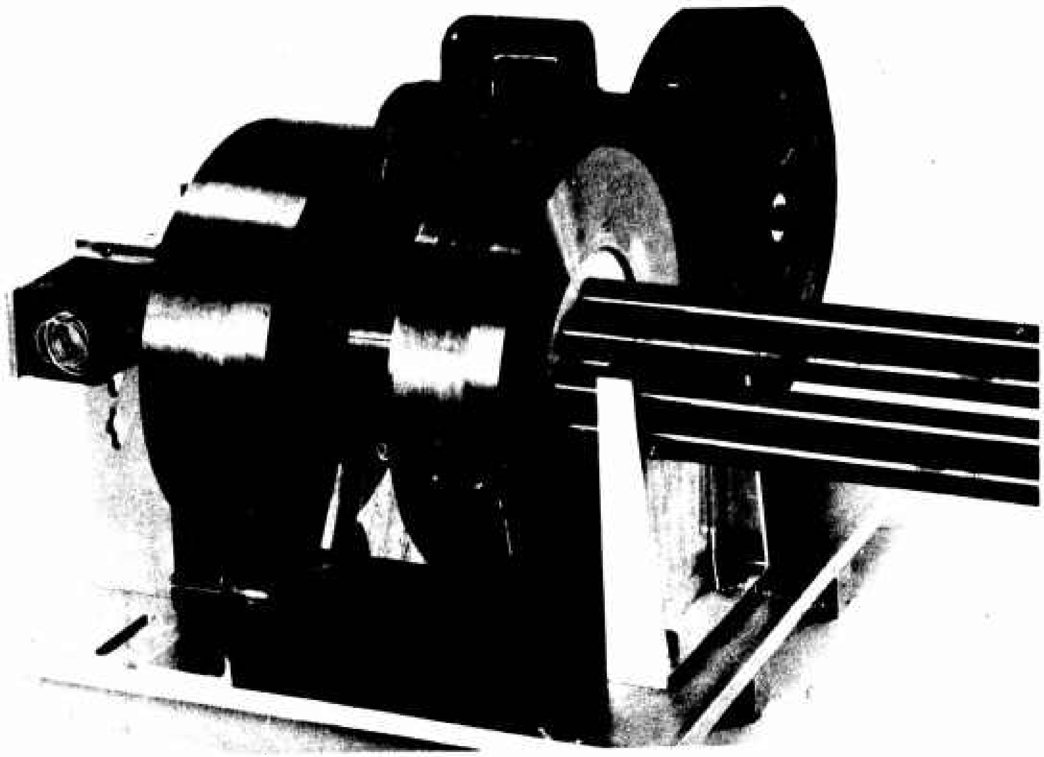

Figure 8. Friction Test Fixture

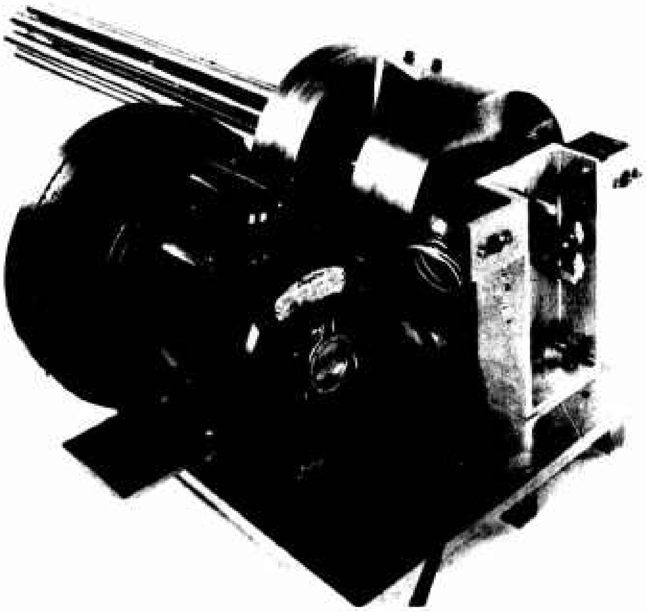

Figure 9. Friction Test Fixture, Rear View

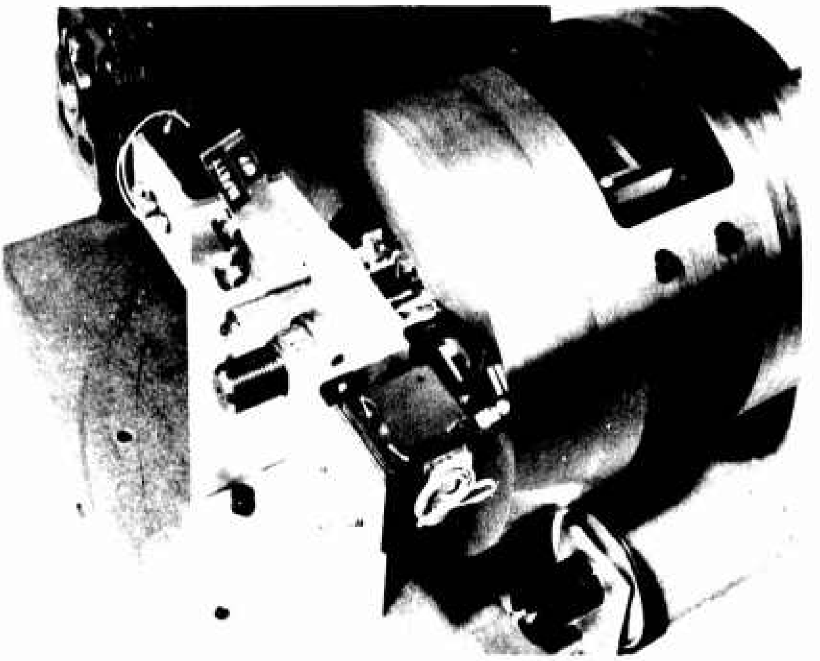

Figure 10. Friction Test Fixture, Firing Mechanism

sequentially and rotates them one-fourth turn for release. Position of the trip lever is such that primer impact occurs while the firing cartridges are covered by the straps. Positive retention of the cartridges on the cylinder is provided by a pair of detachable keepers covering 1/4 in. of either end of the case between the straps.

3.3 ELECTRIC IGNITION SYSTEM

The pulsing unit is based on a Delta Products breakerless automobile ignition system modified to reduce output to nominally 400 V. This is incorporated into a primer-firing system shown schematically in Figure 11. The percussion ignition parts are replaced by the subassembly shown in Figure 12. On the rotating frame, a chopper disc with eight slots interrupts a beam of light which impinges on one end of a fibre optic tube. The other end of the tube is coupled in close contact with the photo diode built into the Delta electronic unit. This is in turn connected to a high tension coil which has its output fed to a distributor plate; the current is transferred by means of a sliding brush. From this point, the current is distributed at the correct moment to the proper firing pin. No mechanical contact is made between the firing pin and the primer on the cartridge, the voltage being sufficient to bridge a small air gap.

3.4 CHECKOUT AND OPERATIONAL PROBLEMS

Prior to firing, cycling tests of the fixture were made to check operation. Several runups were made where the decay rate was recorded.

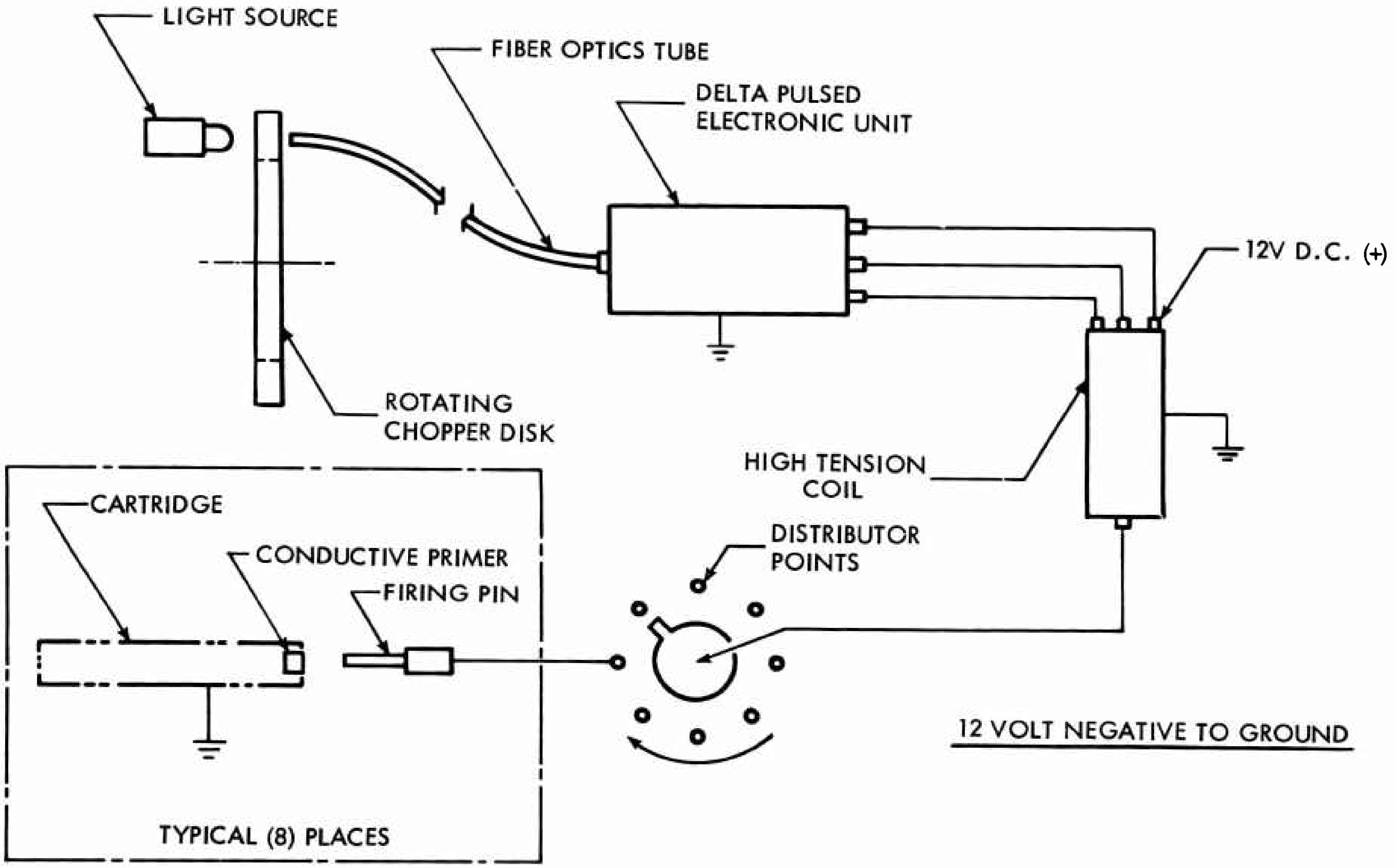

Figure 11. Electric Ignition System Schematic

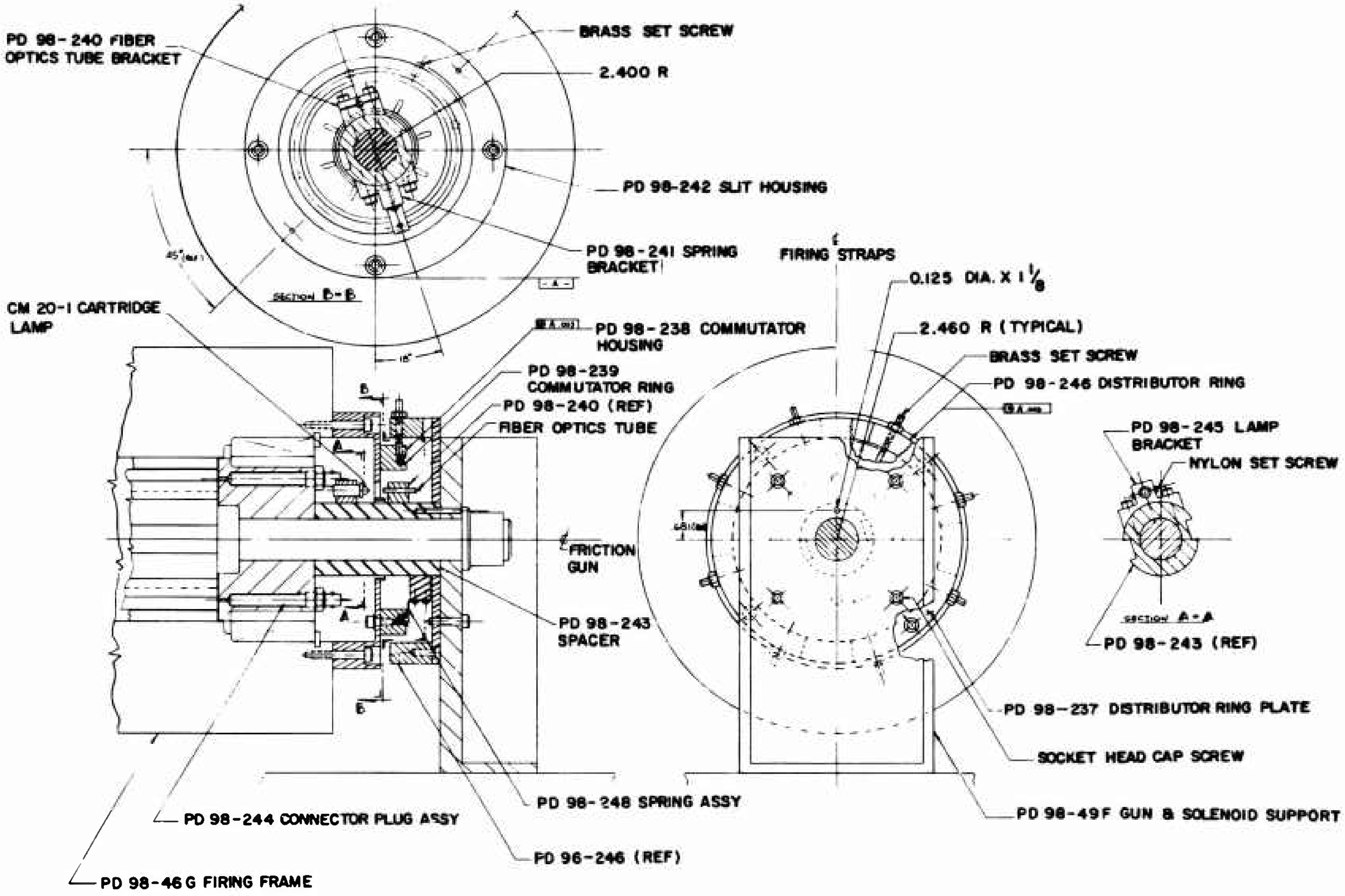

Figure 12. Assembly, Electric Ignition System

This was reasonably uniform as shown by the five traces in Figure 13, as long as only a small amount of light oil was used in the bearings. Bearing friction coefficient was calculated from the slopes of the curves in Figure 13 and fell within the range 0. 001 to 0. 002, which is normal for roller bearings.

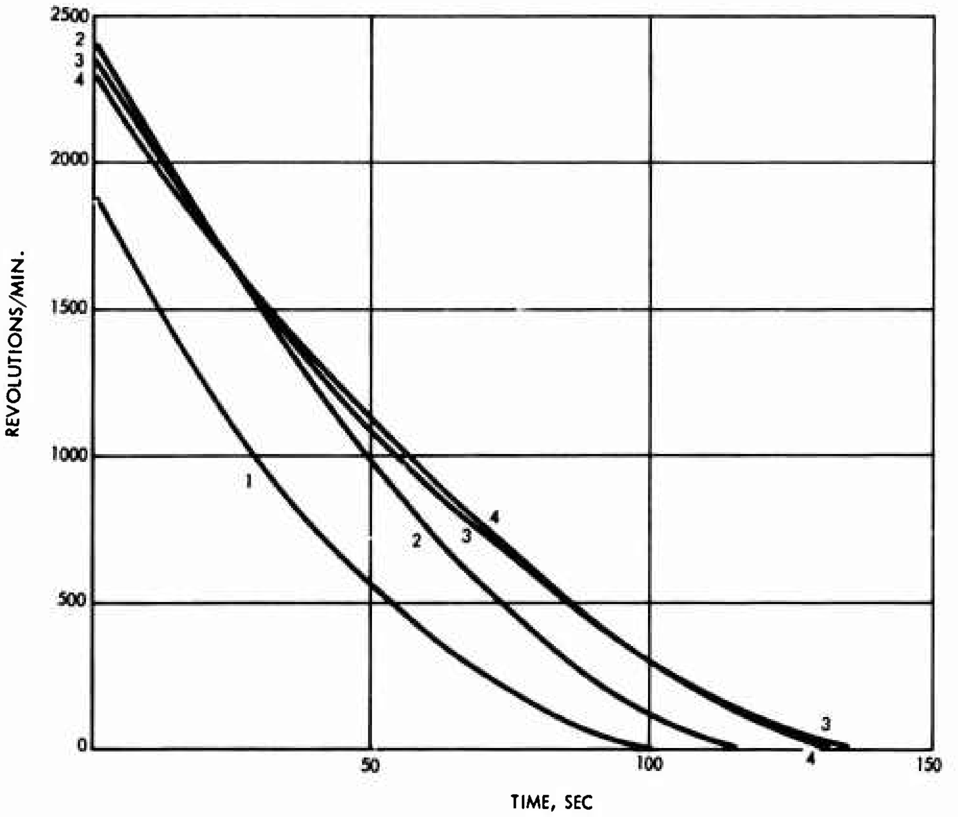

Figure 13. Coasting Rate Decay

The mechanical firing mechanism was cycled successfully at low speed; but at high speed the trip levers malfunctioned or their shafts sheared off. Modifications to the cam surfaces and improved heat treatment did not completely solve this problem, so the trip mechanism design was changed to that shown in Figures 14 and 15. This added an additional link in the release train and reduced loads on all components. The mechanism then operated correctly as verified by high speed movies.

A misfire problem occurred during early firing runs. Since static tests of the pins resulted in reliable ignition, this was difficult to understand. Instrumentation photography revealed elastic bending of the firing pin shafts during release, and rotational overshoot. It also showed that leaking gas from cracked cases was entering firing pin recesses in adjacent chambers and probably retarding fall of the pins. This problem was solved by increasing firing pin stroke and spring tension and providing gas venting cuts on the firing pin spring compression collar.

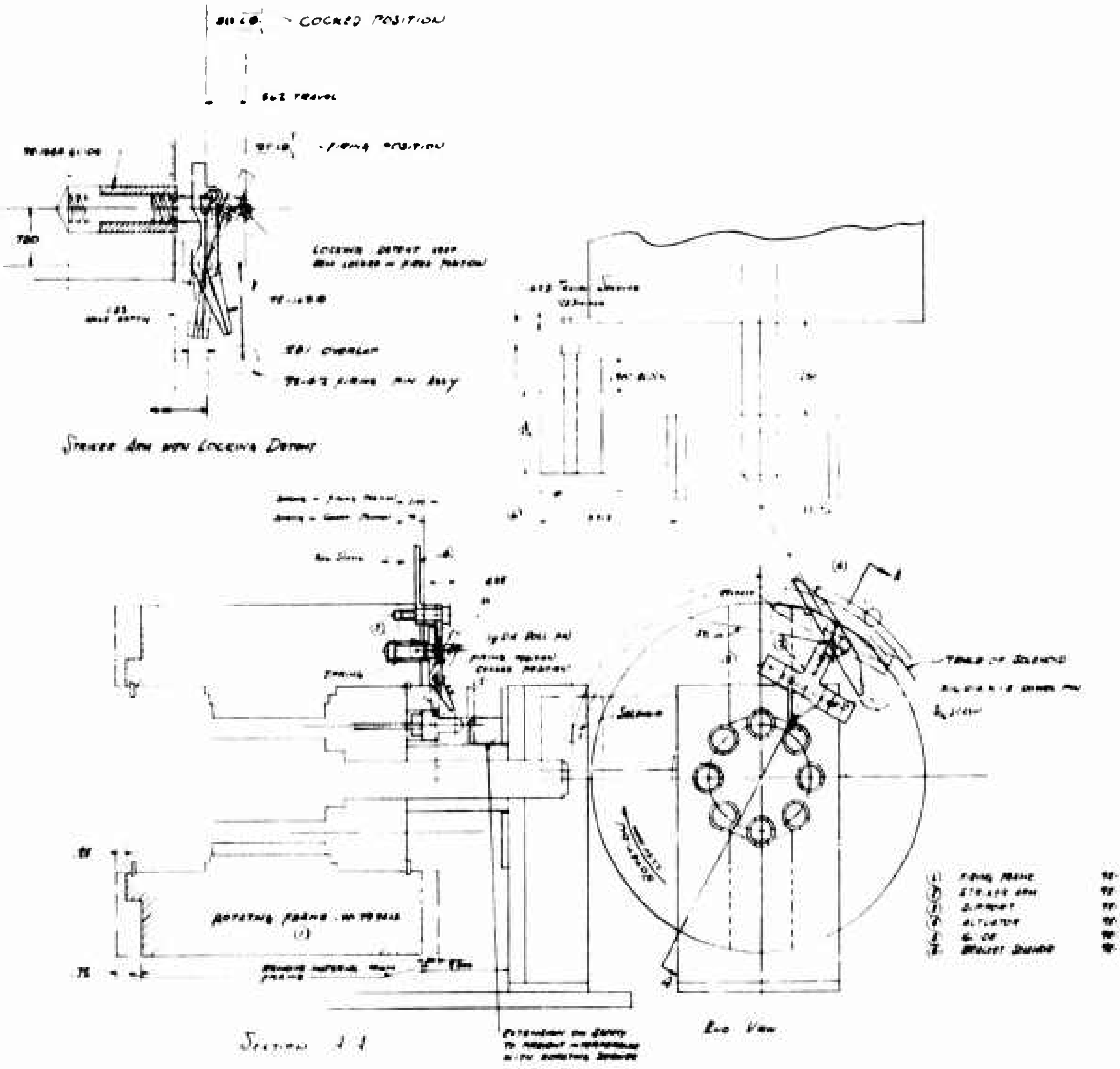

Figure 14. Modifications to Firing Pin Trip Mechanism

Construction and checkout of the electric ignition system was not initiated until late in the program because of uncertainty as to the availability of electric primers. It was found that although the voltage output was nominally 400 V, spikes up to 10,000 V or more occurred. With minor adjustments to the insulation, this caused no apparent problems during low speed checkout. However, when high speed checkout runs were attempted using primed cases, the firing order was erratic due to frequent skips. It was decided to complete tests using percussion-ignited cartridges rather than take time to solve this problem.

3.5 INSTRUMENTATION

The basic measurement taken was rotational rate versus time. From change in rate during firing and the known frame moment of inertia, geometry, and ammunition performance, μ was calculated. Rate was measured by three independent means.

Figure 15. Modified Trip Mechanism Installation

For control of the test, a friction-driven D. C. tachometer was connected to digital or analog meters observed by the operator, who fired when the proper speed was reached during coasting. This output was also recorded on an oscillograph, but was not adequate for data reduction because of zero shifts and intermittent slippage of the tachometer drive wheel relative to the frame.

Rate was also measured by sensing passage of 24 equally spaced pins on the front end of the frame using a magnetic pickup on the mount. This data was recorded as pips on an 80 in. / sec oscillograph trace and reduced using a traveling stage diemakers' microscope to measure precisely the distance between pips.

The third measurement of rate was by 16 mm HYCAM photography at nominally 5000 frames/sec, observing a degree calibration on the rotating frame. These pictures also observed the firing pins and cartridge cases on one side of the gun when not covered by the firing straps. One thousand pulse/sec timing marks on the film allowed accurate plotting of position versus time and, therefore, rate change.

All rate measurements were consistent within the accuracy limitations of the instruments used.

SECTION IV

FRICTION TEST RESULTS

The variables investigated were:

- Rate of fire
- Lubrication of the cartridge cases
- Firing strap material
- Pairs of shots versus all shots under a single strap

Figure 16 is a photograph of the fixture installed in the test cell. This picture shows the electric ignition system and the magnetic rate sensor pins. Table VIII gives the conditions and results for each firing run. On some early runs, excessive misfires or timing problems occurred which rendered the test invalid. In these cases μ was not computed. The physical parameters and method used in data reduction are given in Appendix II. Interpretation and details of each series follow.

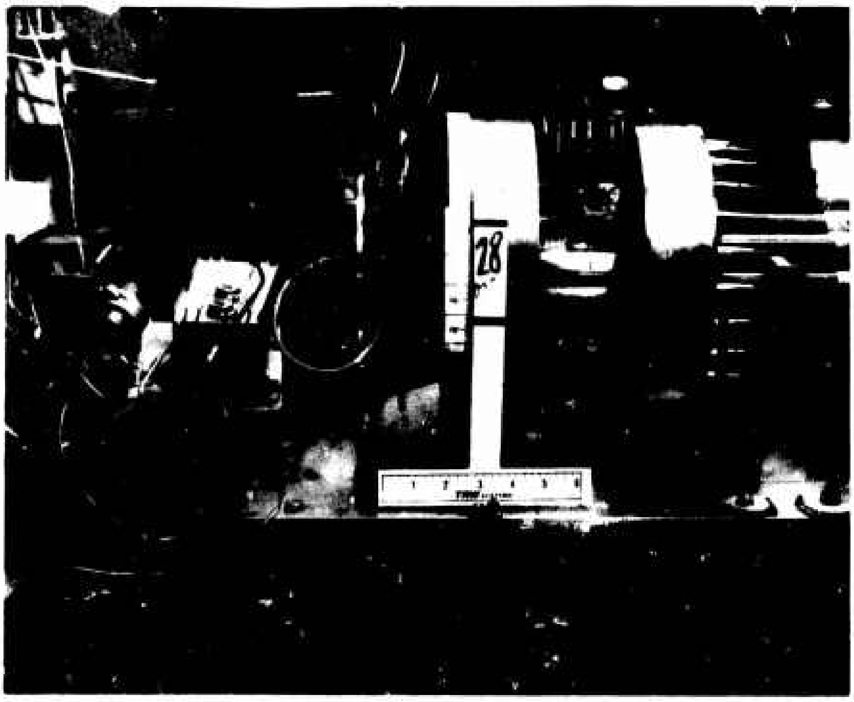

Figure 16. Firing Fixture Installed in Test Cell

TABLE VIII. FRICTION TEST DATA SUMMARY

Run No.	RPM	1 or 2 at a time	No. Misfires	μ	Remarks*
1	1506	2	2	0.043	
2	1463	2	3		Invalid, excessive misfires
3	2198	2	1	0.033	
4	2250	2	5		Invalid, excessive misfires
5	375	2	4		Invalid, fixture timing problem
6	2308	2	1	0.036	
7	2062	2	3		Invalid, excessive misfires
8	1478	2	5		Invalid, excessive misfires
9	1206	2	0	0.030	
10	1504	2	2	0.029	
11	2506	1	0	0.036	Invalid, fixture overspeed
12	2063	2	1	0.036	
13	607	2	0	0.042	
14	489	1	0	0.160	
15	353	2	0	0.132	Possibly invalid, SS strap failure
16	532	2	0	0.083	MoS_2 lube
17	1195	2	0	0.080	MoS_2 lube
18	2181	2	0	0.041	MoS_2 lube
19	1502	2	0	0.040	17-4 stainless strap
20	284	2	0	0.071	17-4 stainless strap
21	822	2	0	0.036	17-4 stainless strap
22	1985	2	0	0.018	17-4 stainless strap
23	581	2	0	0.132	Unicel 100 coating
24	1444	2	0	0.076	Unicel 100 coating
25	2135	2	0	0.052	Unicel 100 coating
26	497	1	0	0.045	17-4 stainless strap
27	1299	1	0	0.083	17-4 stainless strap
28	1408	1	1	0.018	17-4 stainless strap
29	1725	1	2	0.031	17-4 stainless strap

*Uncoated 4340 strap unless noted

4.1 BASIC CONFIGURATION

The configuration used as a basis for comparison employed SAE 4340 alloy steel firing straps and uncoated Lexan cartridge cases. Eight valid runs were made. Figure 17 plots μ against rate in rev/min, shots/sec, and ft/sec sliding speed. Friction coefficient lies in the range 0.03 to 0.04, except for the very lowest speed run where it is 0.16, a value typical of that measured in low speed friction machine experiments. It thus appears that the heating effect is a dominant one, since this low μ is explainable only if surface melting of the Lexan occurs.

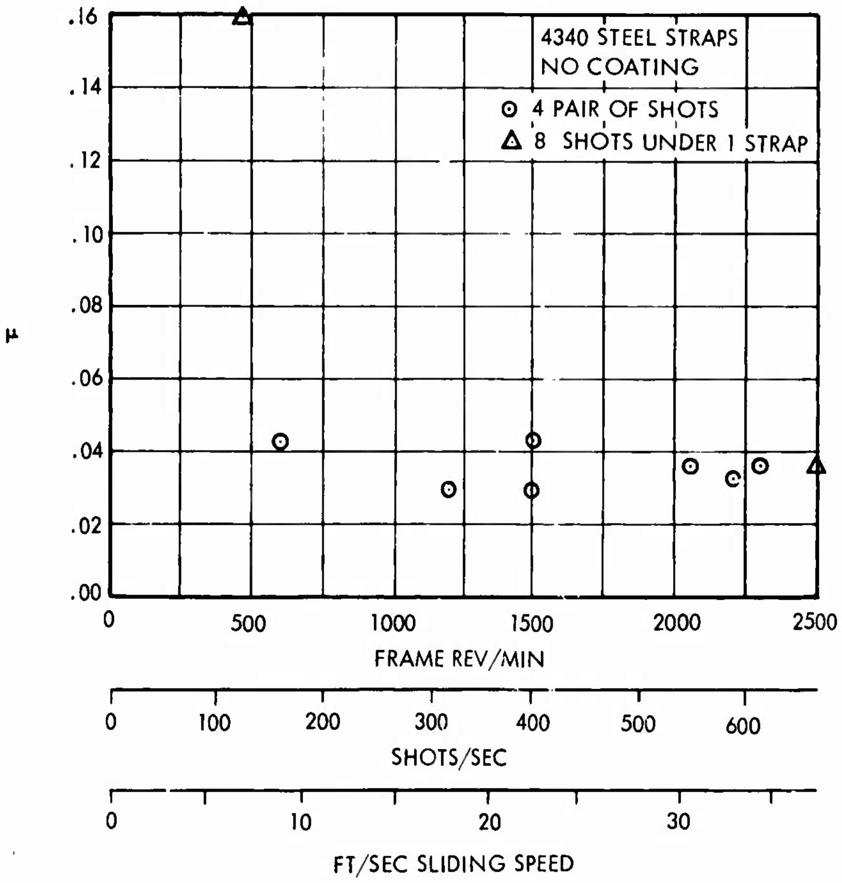

Figure 17. Friction Coefficient Versus Rate, Basic Configuration

4.2 LUBRICATION OF CARTRIDGE CASES

The effect of coating the cartridge cases with the solid film lubricant molybdenum disulphide (MoS_2) was investigated by burnishing the powdered material into the surface of the case and the 4340 strap. Three runs were made and results are plotted in Figure 18. At low speed, a slight improvement was noted compared to uncoated Lexan, since μ is high at low speed where the Lexan surface does not melt. At medium speed, μ was higher than uncoated, indicating the MoS_2 interferred with the surface melting process. At high speed, results were comparable to the uncoated materials.

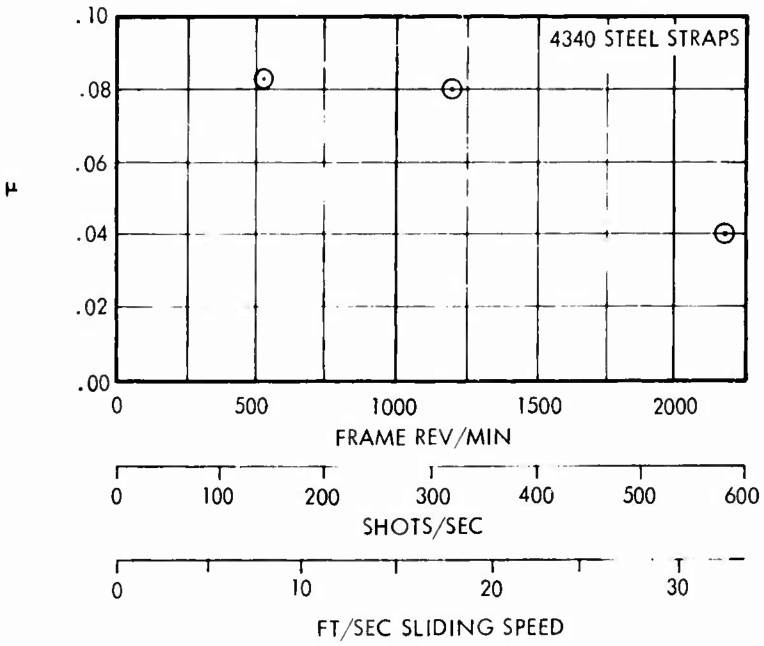

Figure 18. Friction Coefficient Versus Rate MoS_2 Lubricant

4.3 GASING COATING OF CARTRIDGE CASES

Pursuing the melting theory further, if gasing on the case surface could be induced, it might reduce friction even more. Consequently, to test this theory, a surface coating material was sought which would sublime or decompose at a temperature below the melting point of Lexan. The material selected was DuPont Unicel 100 (dinitroso-pentamethylene-tetramine), a "blowing" compound used in the manufacture of foam elastomers. This chemical decomposes at 365°F, yielding gases including over 90% N_2. It is a very finely divided adherent powder and was painted and rubbed onto the cartridge cases. Three runs with cartridges so coated showed that a significant but unwanted effect occurred (see Figure 19); the friction was higher than with uncoated cases. No reasonable explanation is proffered for this result.

4.4 LOW CONDUCTIVITY FIRING STRAP

As shown analytically in Appendix I, thermal conductivity of the firing strap can significantly affect cartridge case heating, and a low conductivity strap should promote early melting of the cartridge case surface and lower friction. This theory was tested by making a series of runs using straps of 17-4 stainless steel. A significant reduction in μ was noted as can be seen in Figure 20, confirming that case melting is a dominant effect.

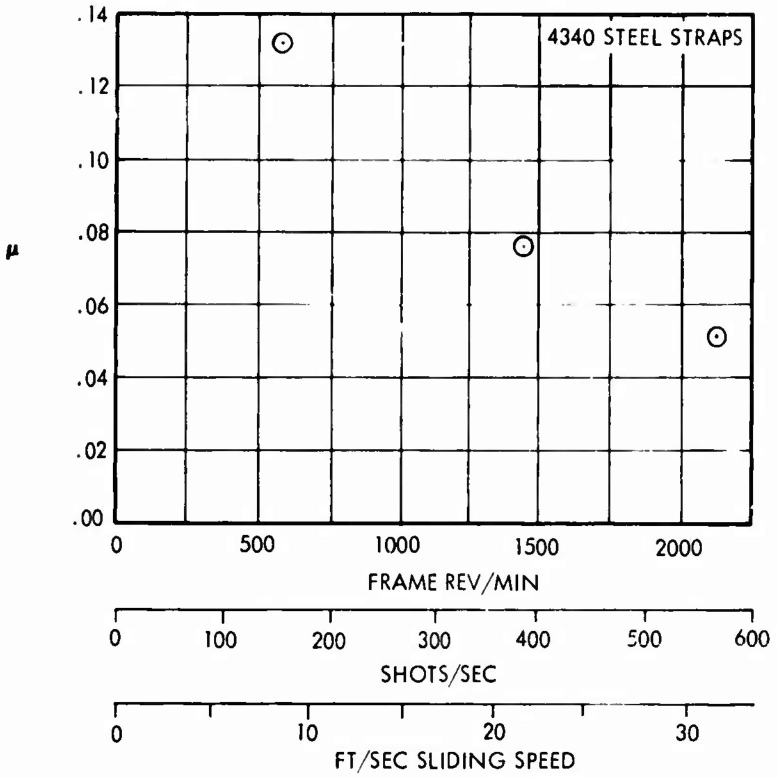

Figure 19. Friction Coefficient Versus Rate, Unicel 100 Coating

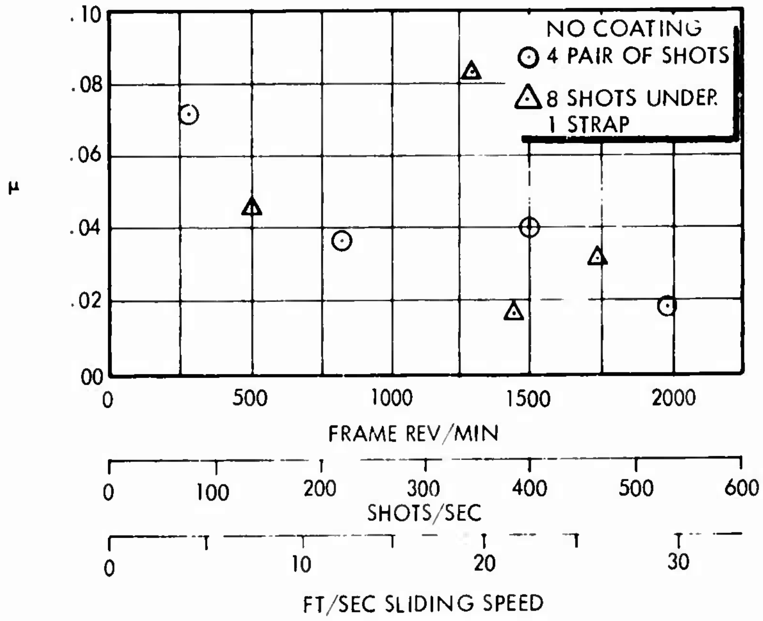

Figure 20. Friction Coefficient Versus Rate, Stainless Steel Firing Strap

SECTION V

SUMMARY AND CONCLUSIONS

5.1 AMMUNITION

Lexan was found to be the only satisfactory case material tested. The stronger glass-filled materials failed due to insufficient elongation, and the weaker materials extruded excessively into the gap between the chamber and firing strap. Lexan also expanded longitudinally sufficiently to seal at the barrel face without a sliding sleeve. The straight Lexan case material used during this program did not tolerate sufficient gap to make scarfing of the firing strap practical; however, the 1% urethane additive shows promise in improved elongation which may make scarfing beneficial.

To obtain satisfactory rear-end sealing, it was necessary to house the primer in a brass cup pressed into a molded-in recess in the case.

A charge of 60 grains IMR 4227 ignited by a magnum large rifle primer and imparting 4600 ft/sec to a 50 grain projectile was selected as the test load. For electric primer initiated cartridges, this was reduced to 57 grains with comparable performance.

5.2 TEST FIXTURE

The friction test gun with percussion ignition system was developed into a reliable fixture capable of measuring μ with adequate accuracy and reproducibility.

The electric ignition system, while unreliable at the present state of development, is probably basically sound in concept.

5.3 FRICTION COEFFICIENT

At rates sufficiently high so that frictional heating of the cartridge case surface causes it to melt, μ falls into the range 0.02 to 0.04. The higher speeds and use of a low conductivity steel for the firing strap promotes melting and tends to reduce μ.

Extrapolation of the data contained herein to other open chamber designs should be based on the relative sliding speed of the case and strap. A change in cartridge case material is probably not significant as long as the melting point and heat capacity of the material are similar to Lexan, as most plastics are.

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APPENDIX I

ANALYSIS OF FIRING STRAP AND CARTRIDGE CASE HEATING

1. FRICTION HEATING RATES

Chamber pressure as a function of time is given in Figure I-1. With two firing stations and a 600 shot/sec firing rate, each firing cycle is 0.00333 sec. The heat generated at the interface between the moving case and stationary strap is equal to:

$$Q = P \cdot A \cdot \mu \cdot V \cdot 4.62$$

where

Q = heat rate (Btu/hr)

P = chamber pressure (psia)

A = area supported by strap (in^2)

μ = friction coefficient

V = relative velocity (ft/sec)

The relative velocity at the interface is 33.3 ft/sec and the area 2.0 in^2. Figure I-2 gives heat dissipation rate as a function of time for a μ of 0.01. Since the heat rate is directly proportional to μ, heating for other μ values can be obtained by multiplying by the ratio of μ over 0.01.

2. FIRING STRAP TEMPERATURE

Because of the low thermal conductivity of the cartridge case and the high relative thermal conductivity of the strap, it can be expected that a larger portion of the heat generated at the interface will go into the strap. If it is assumed that initially the case and strap are at the same temperature and that no phase change occurs in the case, the ratio of heat flow into the case to heat flow into the strap can be closely approximated by:

$$\frac{q_t}{q_s} = \frac{(k \cdot \sqrt{1/\alpha})_t}{(k \cdot \sqrt{1/\alpha})_s}$$

where

q_t = heat rate cartridge (Btu/hr-ft^2)

q_s = heat rate to strap (Btu/hr-ft^2)

k = thermal conductivity (Btu/hr-ft-$^\circ$F)

α = thermal diffusivity (ft^2/hr)

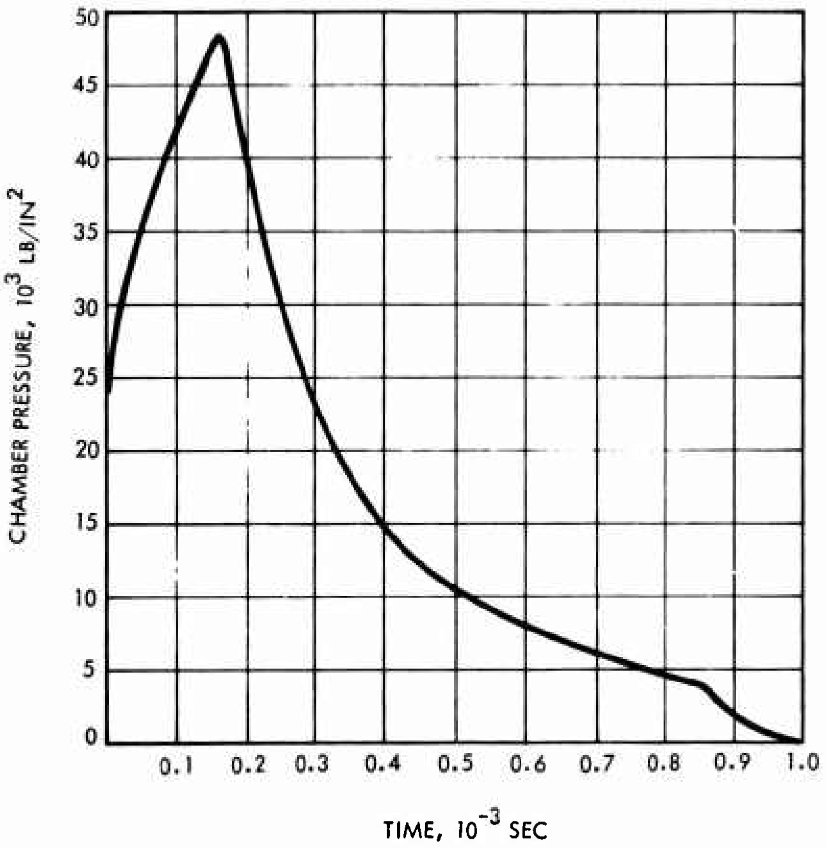

Figure I-1. HIVAP Gun Chamber Pressure Transient

The following values are representative for Lexan (case) and 4130 steel (strap).

Lexan (polycarbonate)	4130 Steel
$k = 0.115$ Btu/ft-hr-^oF	$k = 28$ Btu/ft-hr-^oF
$c_p = 0.3$ Btu/lb-^oF	$c_p = 0.11$ Btu/lb-^oF
$\rho = 75$ lb/ft^3	$\rho = 491$ lb/ft^3
$\alpha = k/\rho c_p = 0.0051$ ft^2/hr	$\alpha = 0.52$ ft^2/hr

With these values the ratio of heat into the case to heat into the strap is 0.041. Based on these results, the temperature of the interface and strap was calculated by assuming that all the heat goes into the strap. Figure I-3 gives temperatures at three positions on the firing strap for μ values of 0.04 and 0.02. These results are based on the average value of heating to the strap. It shows that if μ has a value of 0.04 or greater an overheating problem would occur within about 1 sec.

In order to predict when melting of the Lexan and hopefully a low value of μ will occur, it is necessary to know the surface temperature accurately. The results in Figure I-3 are based on a nodal, lumped parameter analysis. The thermal network is of sufficient detail to give accurate temperatures for firing times greater than about 0.5 sec. A network fine enough to follow individual shot heating transients and to give accurate results for the first few shots would be extremely expensive to run.

For the first few shots, the problem is closely approximated by surface heating of a semi-infinite slab. Analytical solutions are available which predict the transient temperature history for constant heating and for a pulsed heat input. Figure I-4 shows strap surface temperatures for a constant heating rate with the 0.355 msec pulse solution superimposed. Results indicate that for a μ value of 0.04, surface melting of the cartridge case will occur during the second shot. Figure I-5 gives temperature levels for a μ value of 0.02. No surface melting is predicted for the first 10 shots.

Clearly, a strap material which was a better insulator would result in higher interface temperatures for the same friction coefficient. Surface melting of the case would occur at an earlier time. The interface temperature rises is proportional to $\sqrt{\alpha/k}$. Figures I-6 and I-7 give results for a 301 stainless steel insert which has a thermal conductivity of about one-third that of the 4130 steel. Results show that melting of the cartridge case would occur during the first shot. However, as shown in Figure I-7, with a μ value of 0.02, an overheating problem with the strap would occur after about 1.5 sec.

Prediction of surface temperatures has assumed that the entire interface area is in contact. In reality, because of surface roughness, the actual area will be smaller. This would lead to local hot spots, and local melting at the contact areas may occur.

3. RADIANT HEATING THROUGH CARTRIDGE CASE WALLS

Radiant heating from the propellant flame will pass through the case walls and impinge on the straps and firing cylinder. In order to calculate the heating rate, a transmittance measurement was made for the Lexan material. The material has a transmittance of 0.88 in the visible with a cut-off wavelength of about 2 microns.

Assuming a flame temperature of $2700^{\circ}K$ or $4800^{\circ}R$, the integrated transmittance for black body radiation at this temperature is 0.589. Spectral emittance data for the flame combustion products was not found in the literature. However, because of the high pressure involved, a high effective emittance is expected. If a conservatively high value of 0.8 is assumed, the peak heat flux through the case by radiation is 0.875 Btu/sec-in^2. Since the peak friction heating rate at a μ of 0.02 is 40.5 Btu/sec-in^2, radiation heating should have negligible effect on the strap temperature.

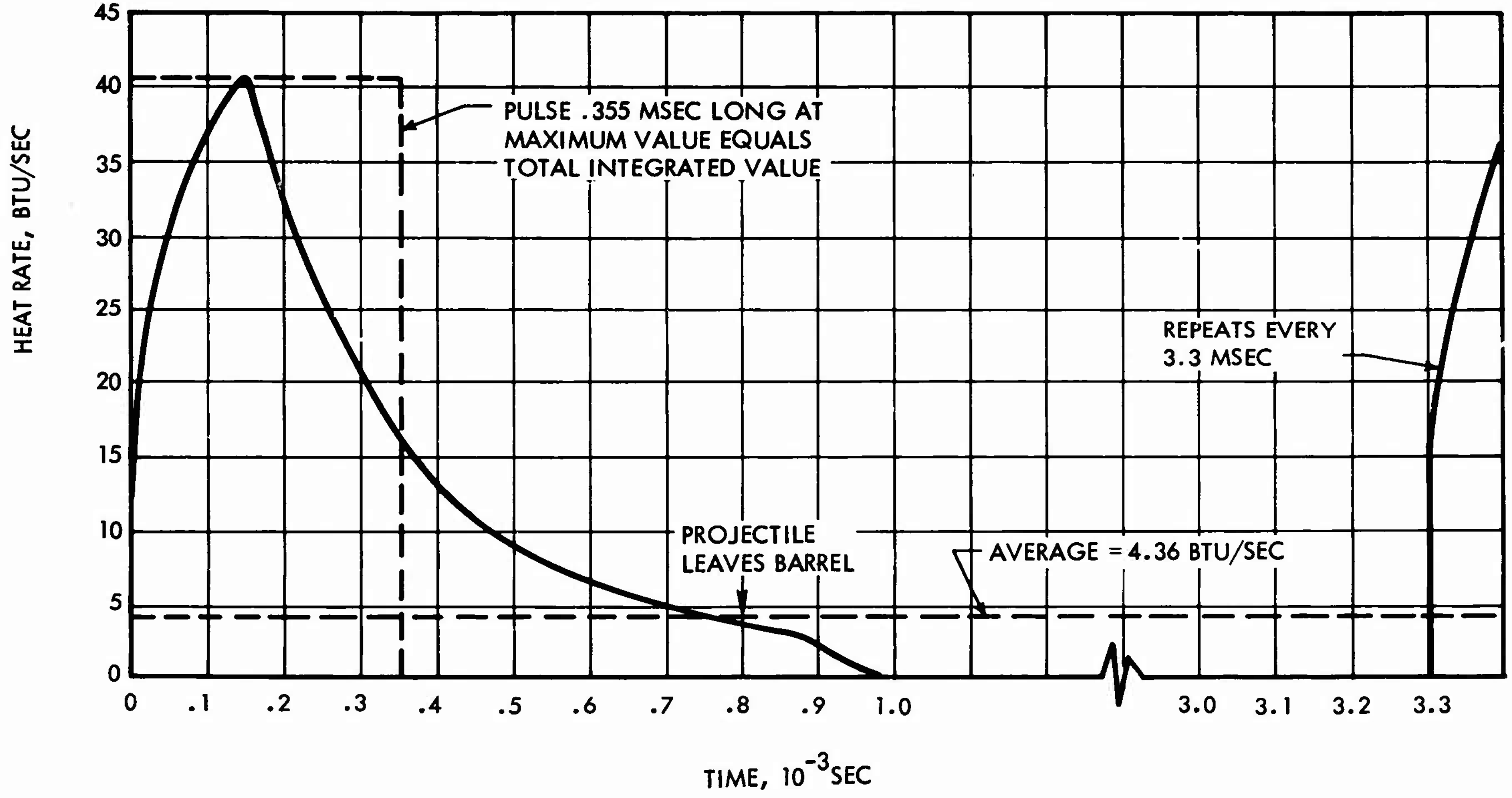

Figure I-2. Firing Strap Heating Rate (μ = 0.01)

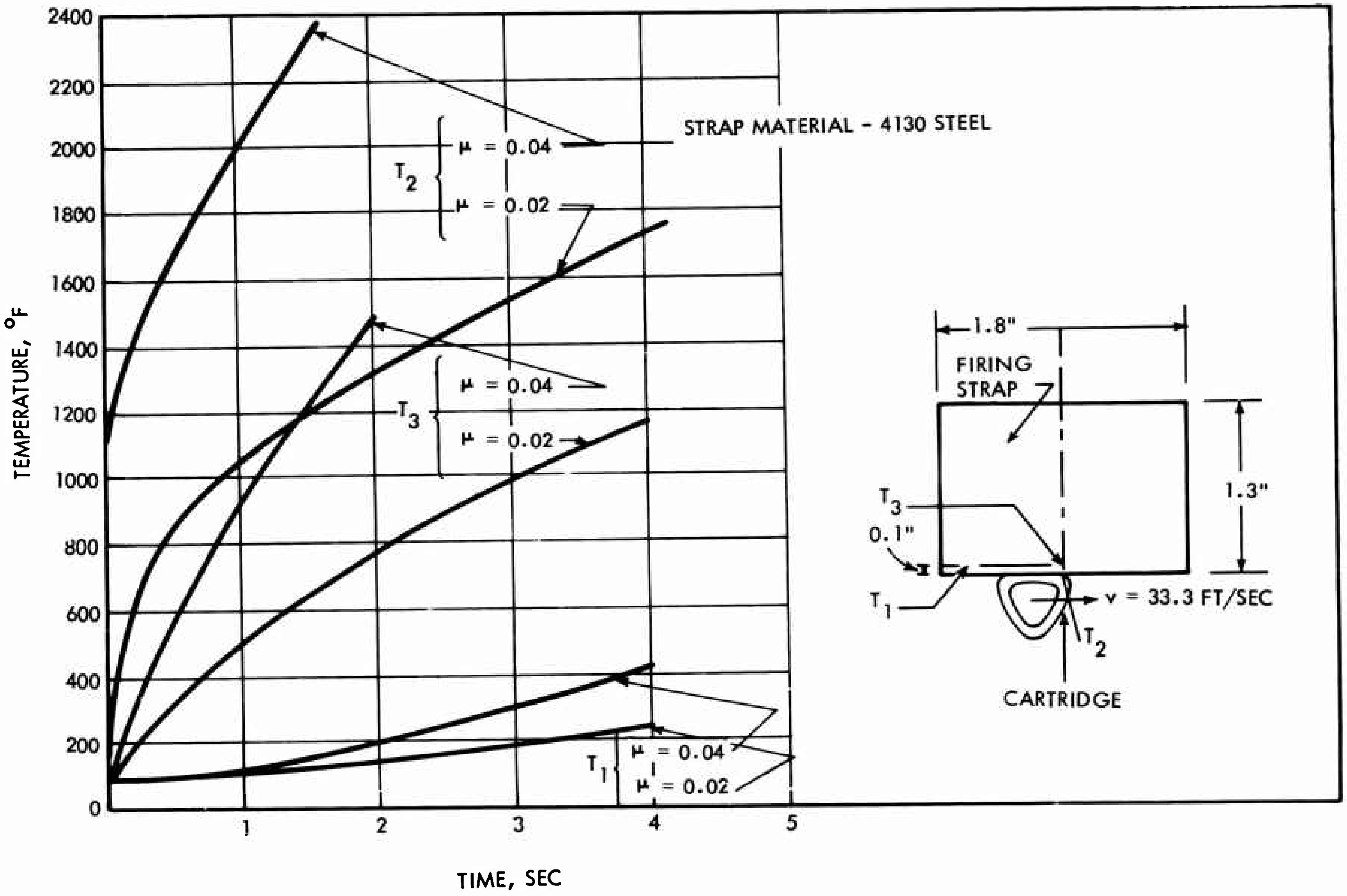

Figure I-3. Strap Average Temperatures

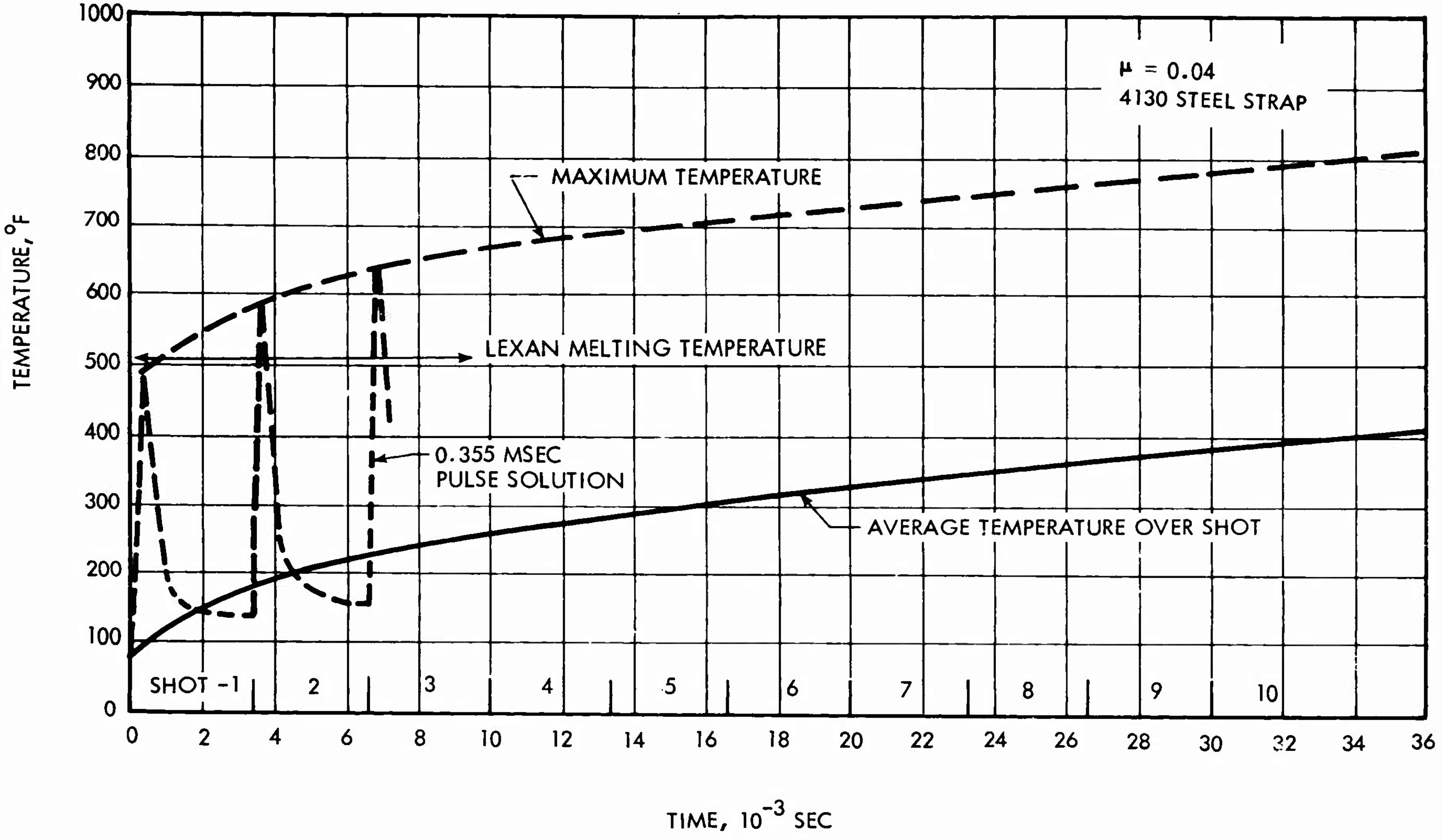

Figure I-4. Strap Temperature History

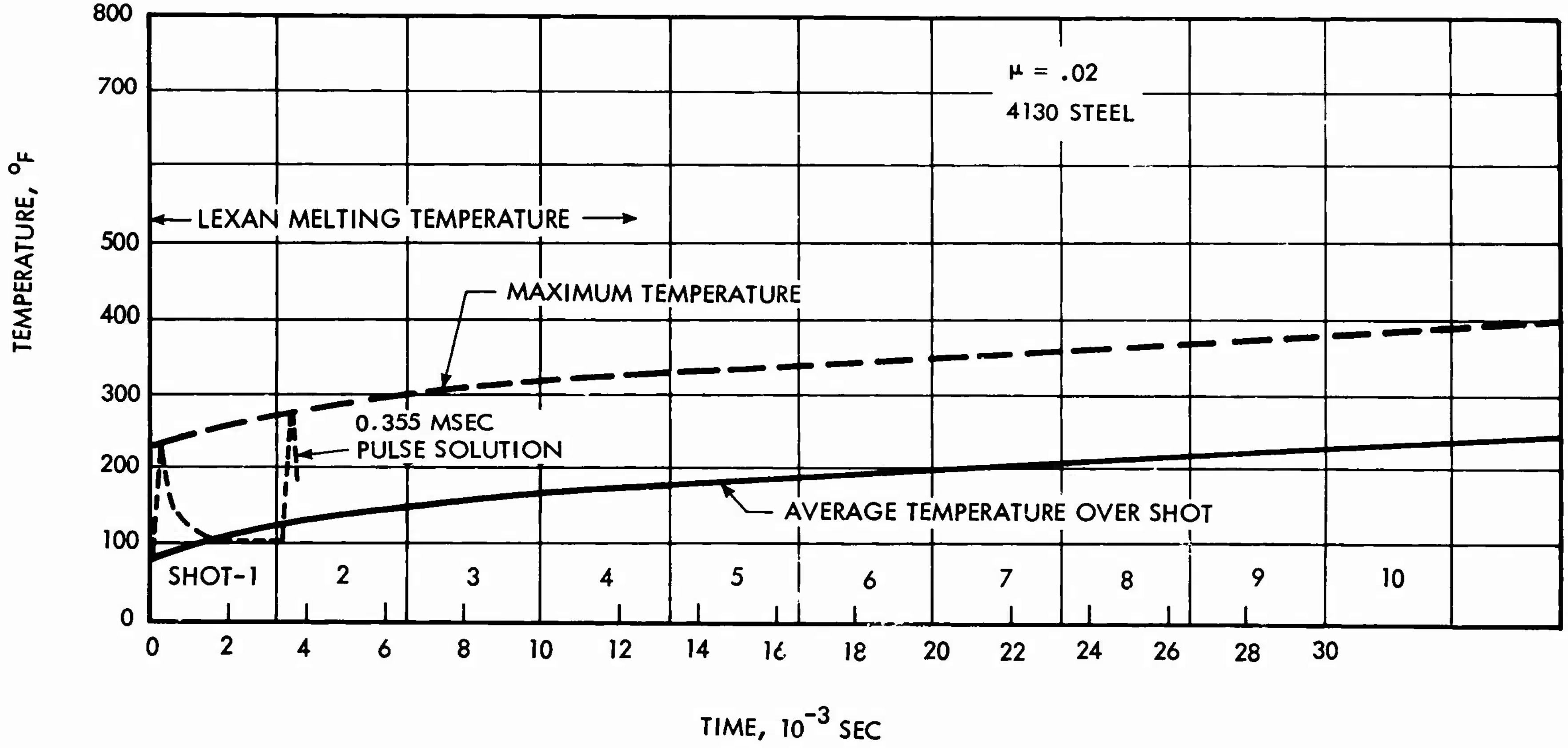

Figure I-5. Strap Temperature History

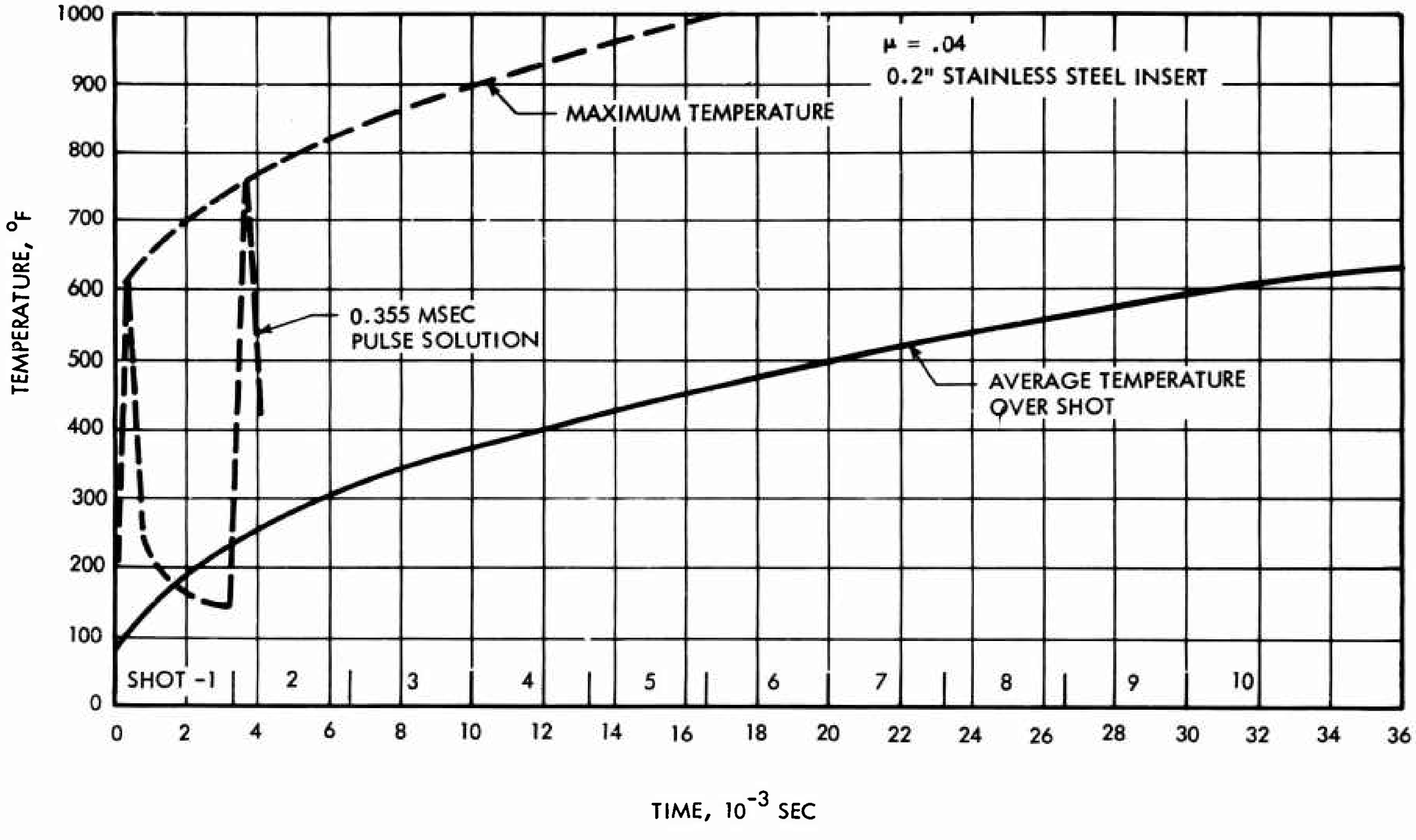

Figure I-6. Strap Temperature

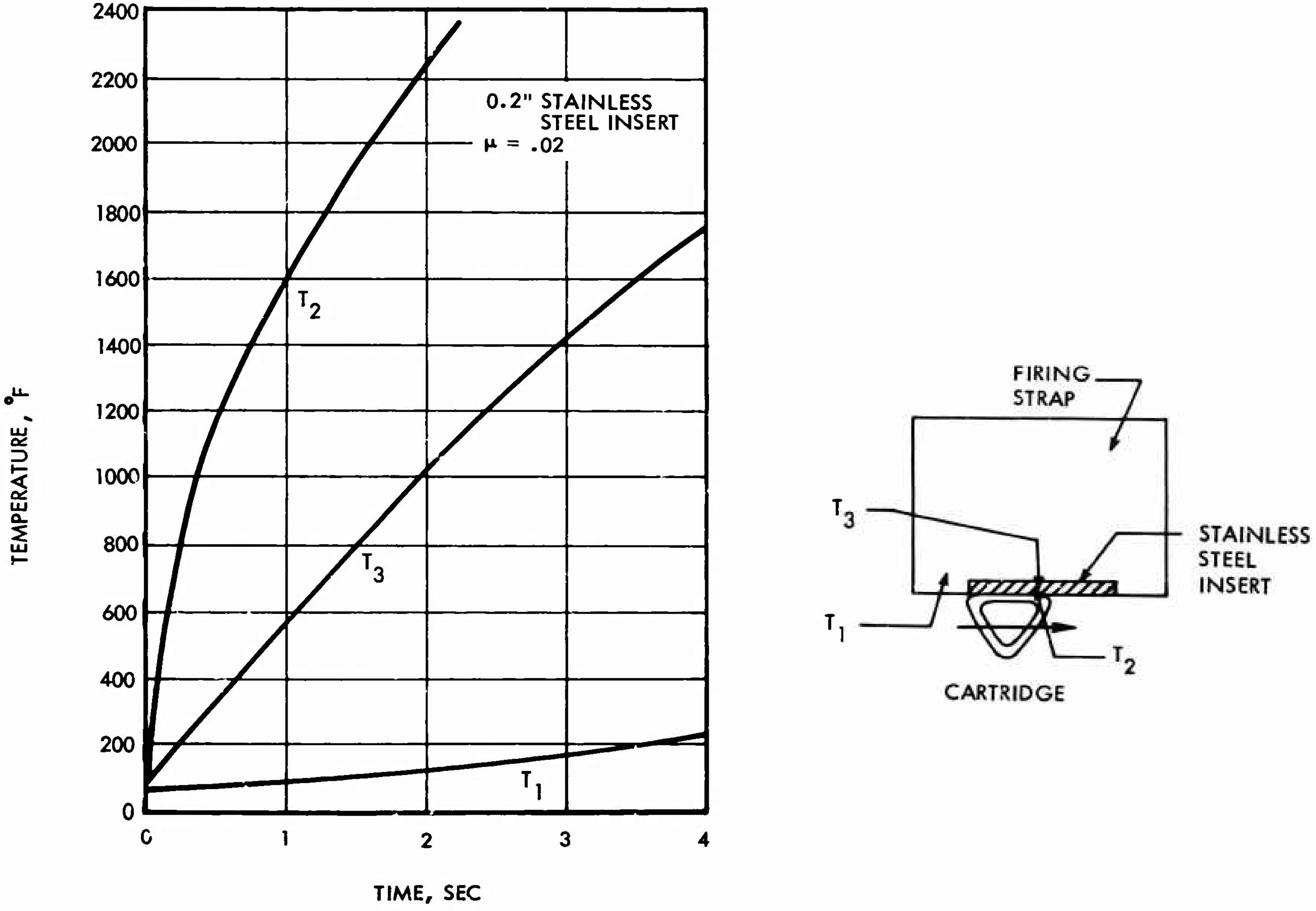

Figure I-7. Strap Average Temperatures

APPENDIX II

DATA REDUCTION METHOD AND PARAMETERS FOR μ MEASUREMENT

Friction coefficient μ is computed from the change in rotational rate of the test fixture frame during firing of the cartridges. The method and pertinent gun and ammunition physical parameters are outlined below.

From Newton's second law of motion:

$$Lnt = I\omega$$

where

L = average drag torque, ft-lb

t = time for shot, sec

I = frame moment of inertia, slug ft^2

ω = change in rotational rate during firing of n cartridges, rad/sec

n = shots

Also,

$$L = Dr$$

where

D = average frictional drag, lb

r = cylinder radius, ft

and, as shown in the introduction,

$$D = PA\mu$$

where

A = cartridge case side area, in^2

P = average chamber pressure, lb/in^2

Thus,

$$\mu = \frac{I\omega}{NtPAr}$$

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13. ABSTRACT

The use of high rate-of-fire open chamber guns could be limited if power required to drive them proves excessive. Drive power is proportional to the gun and cartridge geometry, (rate of fire)^2, and sliding friction between the cartridge cases and the frame members forming the nonrotating parts of the firing chamber. "Handbook" values for friction coefficient do not apply since the bearing pressures and sliding speeds range far in excess of available data for materials of interest. The effects of dissipated heat are also shown to be highly significant since the plastic cartridge cases have a relatively low melting point. An eight-barreled test fixture was designed and built to simulate the conditions of a small open chamber gun firing at rates up to 600 shots/sec. Test ammunition was developed in both percussion and electric-primed versions. Twenty-nine firing tests were made to measure sliding friction while varying rate of fire, frame material, cartridge surface coatings, and number of shots fired. At sliding speeds representing low rates of fire, friction coefficients were comparable to handbook values, that is ~0.16, but above a critical speed the coefficients dropped into the range 0.02-0.04, verifying the occurrence of melting at the cartridge case surface. A dry film lubricant and a low temperature gasing coating were found ineffective in reducing friction. Friction coefficients in the range 0.02-0.04 can be expected for sliding speeds/normal forces high enough to promote melting of the cartridge case surface.

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