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The Behavior of Gun Liners and Coatings Tested under Conditions of Hypervelocity (c) 24683

(None)

Smith, N. H.

Franklin Institute, Philadelphia, Pa. (None)

Office of Scientific Research and Development, NDRC, Washington, D. C. OSRD-6475

t '45 Confd'l U.S. Eng. 223 tables, diagrs, graphs

The caliber .50 erosion testing gun at the Franklin Institute has ben used for the past two years in making firing tests on liners made of a variety of materials and on gun barrels with a variety of coatings. The object of the tests was to discover erosion resistant materials which would prove satisfactory under hyper-velocity conditions, namely at pressures between 58,000 - 53,000 psi (Copper) and muzzle velocities between 3500 - 3300 f.p.s. with a 43"' barrel. This report covers approximatly 130 firing tests in which various materials were used either as liners or coatings. Of these materials, the ones which, as liners, gave promise of being sufficiently resistant to withstand hypervelocity conditions are molybdenum, tantalum and Cr base alloys, and the ones which have similar promise in the form of coatings are chromium and duplex plates with Co or Co-W alloy as an undercoat and chromium as the outer coating.

Copies of this report obtainable from Air Documents Division; Attn: MCIDXD

Ordnance and Armament (22) Gun liners - Erosion-resistant (47411.2);

Guns (2) Gun liners - Materials (47411.14); Gun liners - Effectiveness (47411.11)

C-22-2

Air Documents Division, T-2
AMC, Wright Field
Microfilm No.
RC-977 F24683

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Division 1

National Defense Research Committee of the

Office of Scientific Research and Development

Log 11153

THE BEHAVIOR OF GUN LINERS AND COATINGS TESTED UNDER CONDITIONS OF HYPERVELOCITY

by

N. H. Smith

Franklin Institute

(Contract OEMsr-583)

NDRC Report No. A-404

OSRD Report No. 6475

Pertinent to Projects OD-52 and NO-23

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This is the manuscript of a report that was not edited and duplicated because of the lack of funds and of personnel at the time of the demobilization of OSRD. (See comments appended to the report.)

Copy No.2 of 3 copies 2 October 1945

CONFIDENTIAL

1-B

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Final Report on

THE BEHAVIOR OF GUN LINERS AND COATINGS

TESTED UNDER CONDITIONS OF HYPERVELOCITY

The Franklin Institute

Contract OEM-sr 533

A-404

October 2, 1945

Nicol H. Smith

Associate Director

CONFIDENTIAL

7-B

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CONTENTS

CONFIDENTIAL

3-15

CONTENTS (Continued)

i. 12

TABLES

5P

LIST OF FIGURES

LIST OF FIGURES (Continued)

ABSTRACT

The Caliber .50 Erosion Testing Gun at the Franklin Institute has been used for the past two years in making firing tests on liners made of a variety of materials and on gun barrels with a variety of coatings. The object of the tests was to discover erosion resistant materials which would prove satisfactory under hyper-velocity conditions, namely, at pressures between 56,000 - 58,000 p.s.i.(Copper) and muzzle velocities between 3500 - 3800 f.p.s. with a 45" barrel. This report covers approximately one hundred and fifty firing tests in which the following materials were used either as liners or coatings:

Liners	Coatings
Gun steel	Fluorocarbon
Molybdenum	Parco Lubrite
Monel Metal	
Z-nickel	Oxidized gun steel
Zirconium-nickel	Cu on Cr
Tantalum	Cr on Cu
Silicon Steel	Cr on Ni
Stellite #22	Cr on Ni on Cu
Stellite #21	Cr on (Cr-Cu) alloy
Molybdenum + Nickel	Mo (vapor phase) on steel
Molybdenum + Cobalt	Mo (sprayed) on steel
90 Mo + 10 W	Ni-W alloy
85 Mo + 15 W	Cobalt
80 Mo + 20 W	80 Co + 20 W
60 Cr + 25 Fe + 15 W	86 Co + 14 W
50 Cr + 45 Fe + 5 Mo	82 Co + 18 W
60 Cr + 25 Fe + 15 Mo	Duplex (Co + Cr)
	Duples (Co + W) + Cr
	Mo (vapor phase) on Stellite #21

Of these materials, the ones which, as liners, give promise of being sufficiently resistant to withstand hyper-velocity conditions are molybdenum, tantalum and Cr base alloys, and the ones which give similar promise in the form of coatings are chromium and duplex plates with Co or Co-W alloy as an undercoat and chromium as the outer coating.

8-17

SUMMARY REPORT ON THE BEHAVIOR OF LINERS AND SPECIAL COATINGS UNDER CONDITIONS OF HYPERVELOCITY

A. Experimental Conditions

1. Purpose. The object of the testing program summarized below was to discover a pure metal or an alloy which could be used as a short liner or as a coating in a barrel of gun steel so as to reduce erosion and lengthen the life of the barrel under hypervelocity conditions. All of the tests were made in a caliber .50 Erosion Testing Gun at The Franklin Institute under firing conditions which were chosen so as to give the caliber .50 bullet a hypervelocity, hence the accompanying erosion was produced at a rate which was accelerated in comparison with that usually experienced. Double base powder containing 20% nitroglycerin was used throughout (except where otherwise stated), the exact characteristics required to give the necessary pressure and velocity being determined separately in each test.

2. The Caliber .50 Erosion Testing Gun has the following characteristics:

Length of barrel	45.0"
Volume of powder chamber (pre-engraved bullets)	1.995 in.^{3}
Volume of powder chamber (Ball M2 and A.T. bullets)	1.965 in.^{3}
Travel of projectile	40.8"
Land diameter	0.490" (or 0.500")
Groove diameter	0.510"
Height of lands	0.010" (or 0.005")
Distance from breech to point where lands first attain full height	5.19"

Caliber .50 ball M2 bullets were used in the 0.500" bore and artillery type bullets (banded) and Pre-engraved bullets were used in the 0.490" bore. The chamber, the origin of rifling, and the bullet seat were shaped to receive a 20-mm cartridge case necked down to hold a caliber .50 bullet.

An assembly of the caliber .50 Erosion Testing Gun is shown on Fig. 1.

9-10

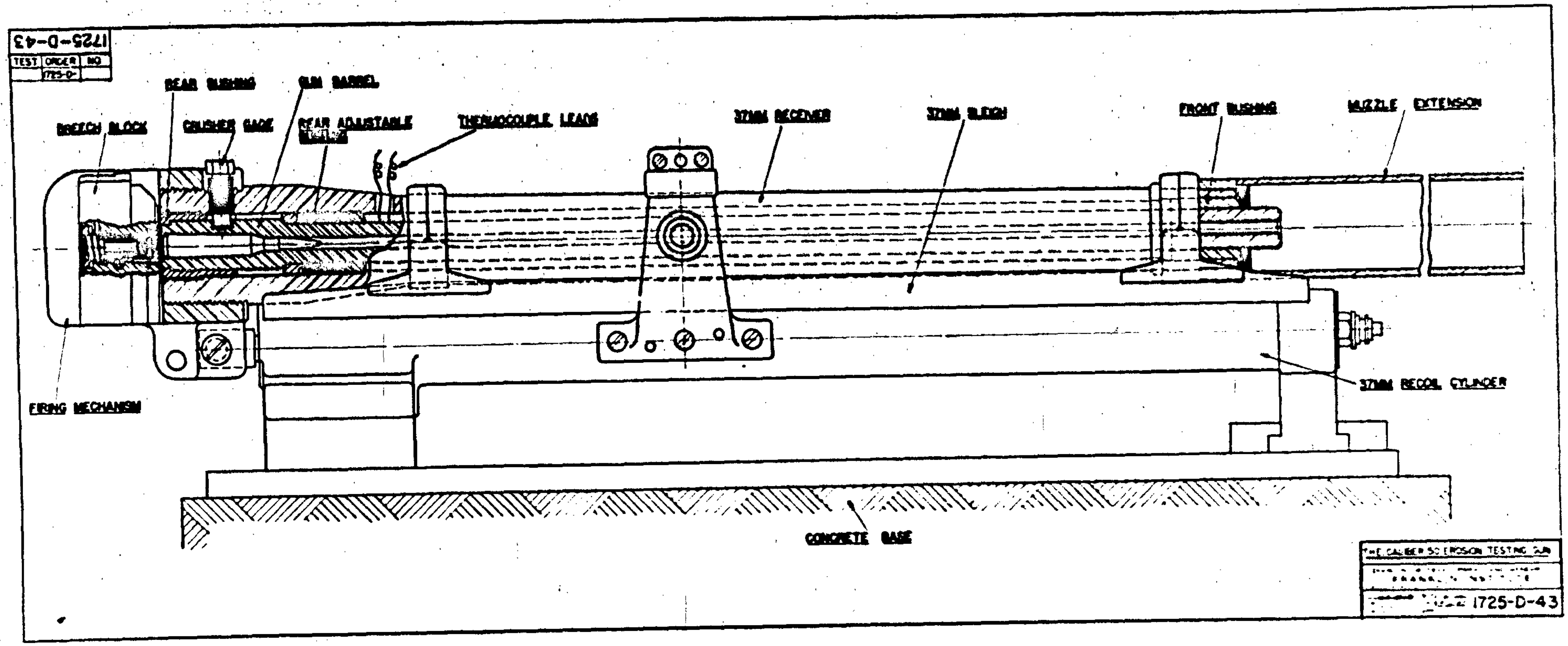

1725-D-43
TEST ORDER NO
BREECH BLOCK
REAR BUSHING
CRUSHER GAGE
GUN BARREL
REAR ADJUSTABLE
THERMOCOUPLE LEADS
37MM RECEIVER
37MM SLEIGH
FRONT BUSHING
MUZZLE EXTENSION
37MM RECOIL CYLINDER
FIRING MECHANISM
CONCRETE BASE
THE CALIBER 50 EROSION TESTING GUN
1725-D-43

FIG. 1

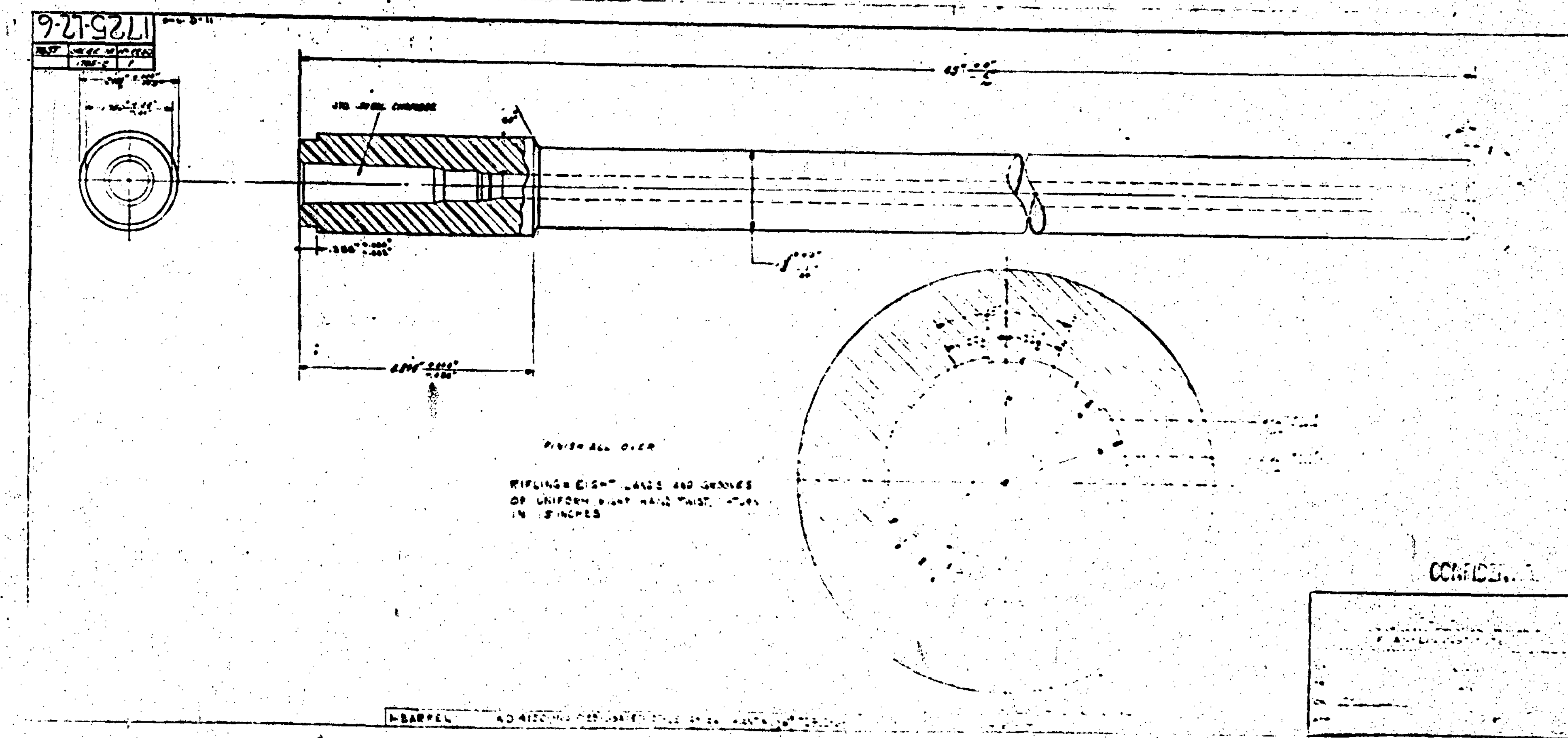


FIG.2

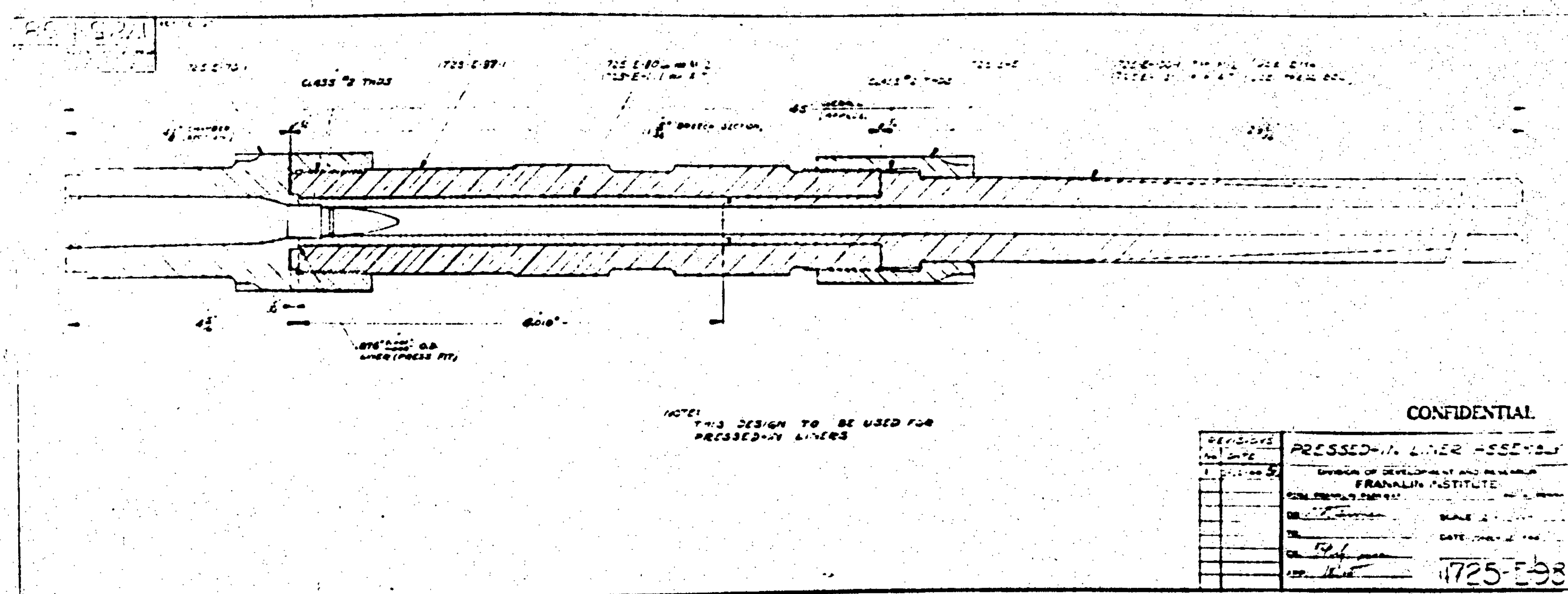

CLASS #2 THDS
.876" O.D. LINER (PRESS FIT)
NOTE: THIS DESIGN TO BE USED FOR PRESSED-IN LINERS
CONFIDENTIAL
PRESSED-IN LINER ASSEMBLY
DIVISION OF DEVELOPMENT AND RESEARCH
FRANKLIN INSTITUTE
1725-E-98

FIG. 3

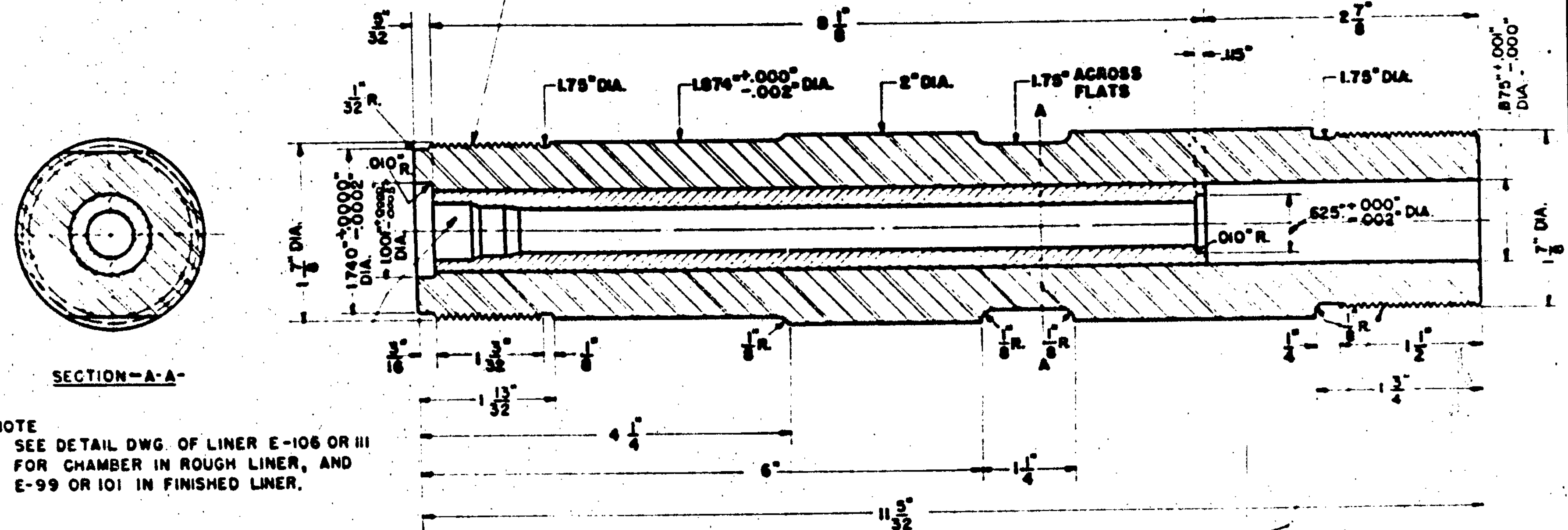
17-B

1725-E-97		
TEST	ORDER	REQD
	1725-E-	1

REF.-1725-E-71 & E-86

NOTE.
12 SPECIAL FINE THDS. PER INCH
CLASS "2 FIT, RIGHT HAND
1.767" MINOR DIA.

NOTE.
ALL BORES MUST BE STRAIGHT, EXACTLY TO SIZES SHOWN, AND CONCENTRIC WITHIN .002". ALL OUTSIDE DIAMETERS MUST BE CONCENTRIC WITH THE BORES WITHIN .003".



NOTE
SEE DETAIL DWG. OF LINER E-106 OR III FOR CHAMBER IN ROUGH LINER, AND E-99 OR 101 IN FINISHED LINER.

NOTE.
FINISH ALL OVER.

NOTE.
12 SPECIAL FINE THDS. PER INCH
CLASS "2 FIT, RIGHT HAND
1.767" MINOR DIA.

FIG. 4

REVISION	
NO.	DATE
1	3-22-44
2	7-26-45

PRESSED-IN LINER
SHOWING LINER IN PLACE IN BREECH

FRANKLIN INSTITUTE

1725-E-97

1-MIDDLE SECTION — GUN STEEL-4150-	1725-E-97-1

13/d

Two types of barrel were used; namely, (1) a 45" monobloc barrel and (2) a 45" liner barrel.

A description of the 45" monobloc barrel is shown on Fig. 2

A description of the 45" liner barrel and the pressed-in liner in place in the carrier section, is shown on Fig. 3 and Fig. 4.

The Caliber .50 Erosion Testing Gun is described completely in the report on the erosion testing gun.

3. Conditions of Firing.

(a) Powder. In each test the necessary conditions of hypervelocity were attained by adjusting the charge as the result of measurements made on the maximum pressure, during the first few rounds. By combining a certain per cent of "slow" powder with the complementary per cent of "fast" powder (differing in web thickness), it was possible to adjust the resultant characteristics so as to create a maximum pressure within the range 56,000-58,000 psi.(Copper) using the same weight of powder. The double base powders used were made by the Hercules Powder Co. and the single base (IMR type) powders were made by du Pont. The characteristics of these powders are given in Table I below:

Table I - Characteristics of Powders Used in Hypervelocity Tests

Constituent	HES 1770.243	HES 1770.107(#9)	Ex 5098
Nitrocellulose	77.83	74.08	86.70
Nitroglycerin	—	18.83	—
Dinitrotoluol	—	—	8.74
Potassium Sulphate	1.09	0.99	0.65
Graphite	0.23	0.36	—
Diphenylamine	0.76	0.58	0.77
Moisture	0.68	0.60	1.11
Total Volatiles	—	—	1.57
Coating (added)	1.72	4.92	(DNT)
Residual Solvent	—	—	0.45

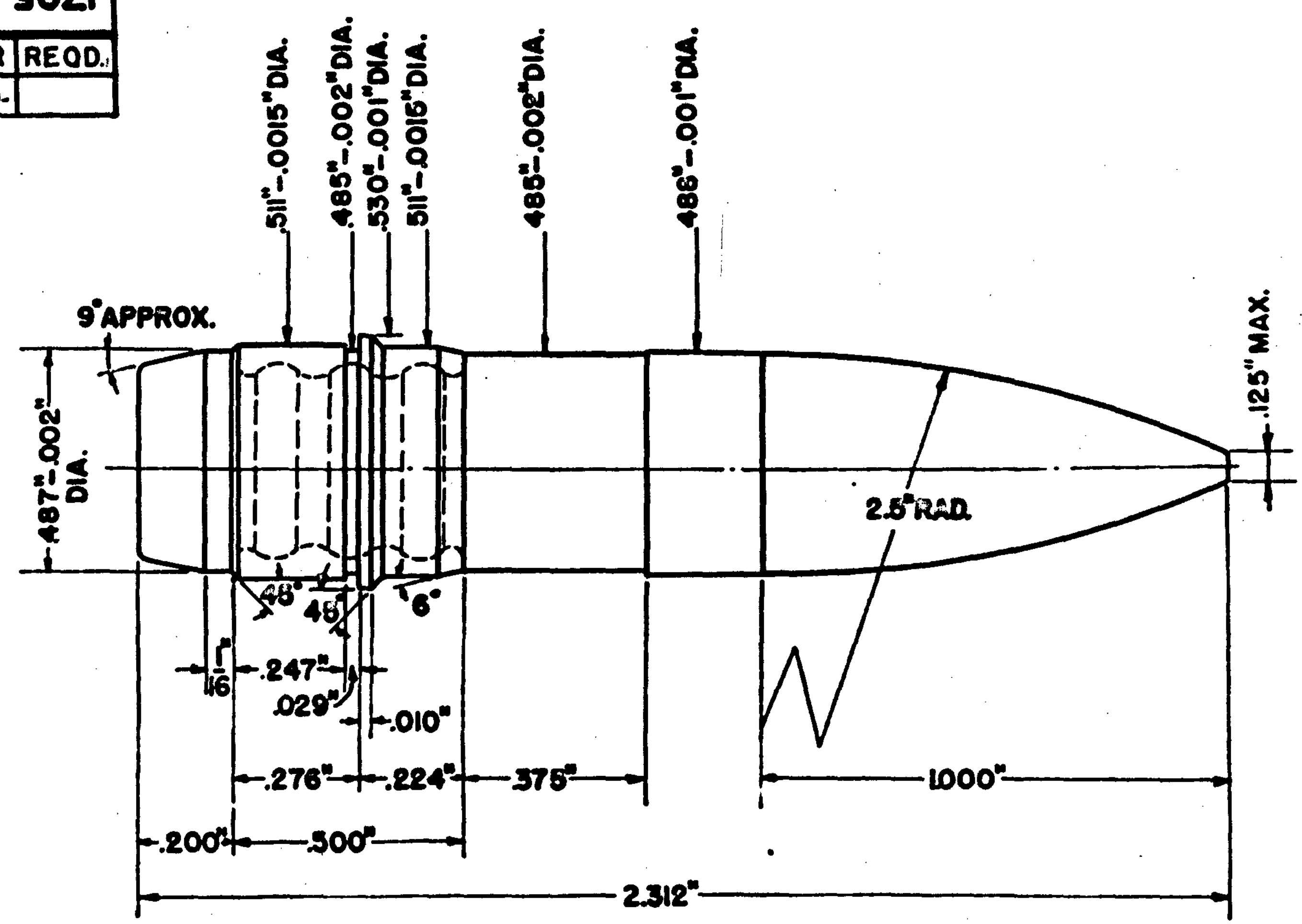


FIG. 5

TEST	ORDER	REQD.
	1725-J-	

1725-A-30-A-

1-BAND—HARD DRAWN COPPER TUBING —	1725-A-30-A-3
1-BODY—SOFT STEEL, X1112—	1725-A-30-A-2
1-BULLET (COMPLETE)—FIN. WT. 700 TO 710 GRAINS—	1725-A-30-A-1

½ BANDED RING SEAL TYPE
A.T. CAL 490 PROJECTILE

DIVISION OF DEVELOPMENT AND RESEARCH
FRANKLIN INSTITUTE

DATE 9-14-45

1725-A-30-A

15-13

1725-LI-5

TEST	ORDER	REQD.
T-160	1725-LI-	1

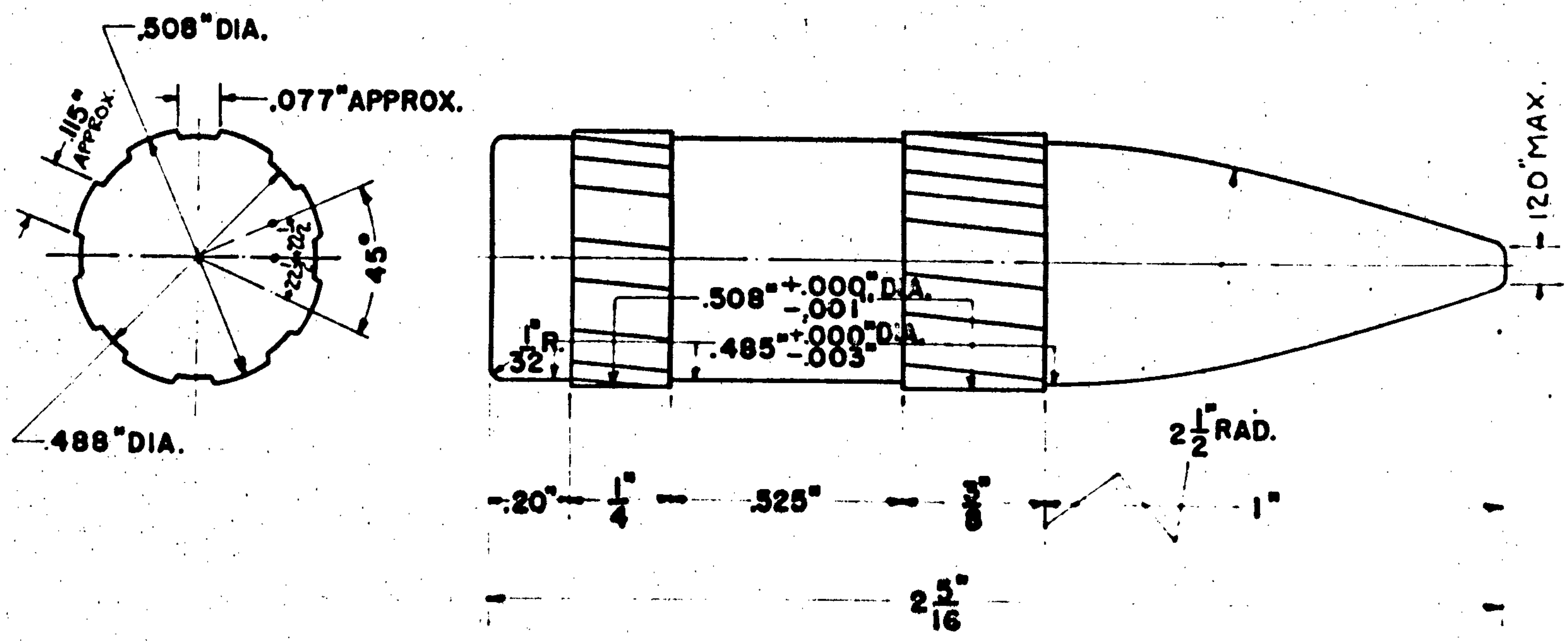


FIG. 6

REVISIONS	
NO.	DATE
1	12-31-43
2	1-8-44

50 CAL. P.E. BULLET
.490" BORE

DIVISION OF DEVELOPMENT AND RESEARCH
FRANKLIN INSTITUTE

DR. G.N. Saccas — SCALE: 36" = 1"
DATE: 9-26-45

1725-LI-5

1-BULLET — SOFT STEEL — 1725-LI-5-1

16-13

Table I (Continued)

Grain Dimensions	HES 1770.243	HES 1770.107(#9)	Ex 5098
Length (inches)	0.1735"	0.0906"	0.0836"
Diameter (inches)	0.1561	0.0582	0.0699
Dia. Perforation	0.0109	0.0064	0.0071
Web (outer)	0.0331	—	—
Web (average)	0.0309	0.0259	0.0321
No. of Perforations	7	1	1

(b) Bullet. A majority of the tests were fired with caliber .50 Ball M2 bullets weighing 700±10 grains, but in some cases either pre-engraved bullets or those of artillery type (banded) were used. The weights of the P.E. and A.T. bullets were also maintained at 700±10 grains.

The shape and dimensions of the artillery type (copper banded) bullet are shown on Fig. 5.

Pre-Engraved bullets (P.E.) were used in tests to eliminate engraving stresses and determine the resistance of the material to powder gas erosion alone. The shape and dimensions of the steel banded pre-engraved bullet are shown on Fig. 6.

(c) Rate of Fire. Two firing schedules were adopted as standard, one of 35 rounds and one of 70 rounds. These schedules are designated as Schedule I and Schedule II.

Schedule I (1) 10 rounds, pressure and velocity
" I (2) 20 " , erosion
" I (3) 5 " , bullet recovery

Schedule II (1) 10 rounds, pressure and velocity
" II (2) 55 " , erosion
" II (3) 5 " , bullet recovery

The rate of fire was 4 rounds per minute. At the end of the schedule the bore was examined, photographed and gaged. This process was repeated until the total number of rounds was reached.

17-12

For the testing of the Mo liners more severe schedules were adopted. These schedules are described under the chapter related to Mo liners.

For the testing of the Mo plated liners less severe schedules were adopted. These schedules are described under the chapter related to Mo plated liners.

(d) Pressure and Velocity. The word "hypervelocity" is used in this report to indicate a velocity within the range 3500-3800 fps. when a new 45" barrel is used. In order to give a caliber .50 bullet such a velocity the maximum pressure in the barrel must lie within the range 56,000-58,000 psi.(copper). As erosion proceeds both pressure and velocity fall, but the conditions of these tests were such that the initial velocity lay within the prescribed range for each.

Measurements of maximum powder pressure were made by means of a copper cylinder crusher gage, the accuracy of which is estimated at 5%. These "copper" pressures differ by about 20 per cent from the true piezoelectric measurements of pressure.

Measurements of velocity were made by means of two screens 37 ft. apart connected to an Aberdeen type chronograph. The first screen was 8 ft. from the muzzle of the gun. The accuracy of this equipment is estimated at 0.5%. The velocities reported, therefore, are instrumental velocities at 26 feet from the muzzle.

4. Properties of Liners and Coatings. An examination of the physical properties of metals and alloys, supplemented by vent plug tests,(1)

(1) A-148. "Metals Tested as Erosion Vent Plugs" by Loeffler, Phair and Jerabek.

has indicated that certain ones might possess the requisite characteristics for use as a short liner in a barrel of gun steel. Since the behavior of a given metal in a vent plug test often differs significantly from its behavior in an actual firing test, liners, varying in length usually from 5 to 8 inches, were made and introduced into the Erosion Testing Gun. The pure metals and the alloys listed in Table II, together with some of their physical properties, were thus tested in the form of liners.

Table III shows the chemical composition of the gun steel used as a control and several alloys used in making liners.

The properties of an ideal erosion-resistant material are well described in the Report of the Resistant Materials Committee of Division One, 15 January 1944, page 8, as follows:

"(1) A combination of high melting point, high specific heat and high thermal conductivity, such that the maximum temperature attained by the bore surface will always be well below the melting point of the material.

"(2) A high resistance to chemical reaction with the powder gases at the temperatures attained by the gases and the bore material.

"(3) A high resistance to thermal shock as evidenced by a minimum tendency to crack under the rapid heating and cooling cycle.

"(4) A high resistance to mechanical abrasion.

"(5) A hot hardness sufficiently high to prevent plastic deformation of the rifling under the engraving stresses at the maximum temperature attained by the bore surface."

19-10

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TABLE II — PHYSICAL PROPERTIES OF MATERIAL USED AS LINERS AND COATINGS

Material	Tensile Strength x 10³ (psi)	Yield Point x 10³ (psi)	Coefficient of Expansion x 10⁶ (per °C)	Coefficient of Thermal Conductivity [illegible]	Melting Point (°C)	Hardness		
						[illegible]°C	[illegible]°C	600°C
Gun Steels:								
SAE 4140	114[1]	[illegible][1]	[illegible][12,A]	[illegible][8]	145[illegible][8]	-	-	-
SAE 4150	[illegible][1]	[illegible][4]	[illegible][12]	-	145[illegible][8]	[illegible][4,V]	[illegible][4,V]	14[illegible][4,V]
Stellite Steel	14[illegible][1]	[illegible][1]	15[A]			[illegible][5,B]	[illegible][5,B]	[illegible][5,B]
Monel Metal	[illegible]-125[1]	[illegible][1]	15.[illegible] 16.[illegible][5]	0.0[illegible][5,A]	13[illegible][A]	16[illegible][1,B]		
Stellites:								
#6		-	15.2[5]	-	-	442[2,V]	2[illegible][2,V]	297[2,V]
#21	[illegible][5]	[illegible][5]	17.6[5]	-	1250-13[illegible][5]	316[5,V]	1[illegible][2,V]	161[5,V]
#22	[illegible][11]	93.5[11]		-	-	383[2,V] 444[11,V]	353[2,V] 335-469[11,V]	246[2,V]
[illegible]-Nickel	16[illegible]-180[1]	120-14[illegible][1]	-	-	-	24[illegible][4,V]	318[4,V]	2[illegible][4,V]
Chromium:								
High Contract.	-	-	8.11[6]	-	1615[6]	370[7,V]	-	-
Low Contract.	-	-	-	-	-	647[7,V]	-	-
Cobalt (Cast)	34[6]	-	12.3[6]	0.165[6,A]	1480[6]	86[6,B]	-	-
Copper (Cast)	14.2-17.5[6]	-	16.7[6]	1.045[5]	1083[6]	40[6,B]	-	-
Molybdenum:	236-315[5]	-	5.7[10]	0.346[5]	2620[6]	235[4,V]	136[4,V]	128[4,V]
Hot rolled	88.6[8]	68.5[8]	-	-	-	250[8,V]	-	-
Wrought, Swat.	90-100[8]	60-70[8]	5.49[8]	0.350[8]	-	260-270[8,V]	-	-
Tantalum	182.5[5]	-	6.5[5]	0.130[5]	2850[6]	75-125[1,B]	-	-
Tungsten	597.4[5]	-	4.5[5]	0.476[5]	3370[6]	-	-	-
90 Mo + 10 W:	-	-	-	-	-	288[2,V]	160[2,V]	153[2,V]
Hot rolled	127[8]	-	-	-	-	-	-	-
85 Mo + 15 W	-	-	-	-	-	249[2,V]	198[2,V]	185[2,V]
80 Mo + 20 W	-	-	-	-	-	268[2,V]	191[2,V]	196[2,V]
60 Cr + 25 Fe + 15W	-	-	<4.9[4]	-	1750[4,A]	450[4,V]	-	-
50 Cr + 45 Fe + 5Mo	-	-	>4.9[4]	-	1540[4,A]	360[4,V]	-	253[4,V]
60 Cr + 25 Fe + 15 Mo	-	-	4.9[4]	0.[illegible][4]	1700[4,A]	478[4,V]	-	420[4,V]

Source of Data:

1. Metals and Alloys Data Book. Hoyt. 1943.
2. Report of Committee on Resistant Materials. June 1, 1944.
3. Haynes-Stellite Company
4. Climax Molybdenum Company.
5. Handbook of Physics and Chemistry, 1944.
6. International Critical Tables.
7. Report of Committee on Resistant Materials. January 15, 1944.
8. NDRC Report #A-273 on Molybdenum. Brace and Harden. May 1944.
9. U. S. Army Specifications.
10. Geophysical Laboratory Report No. A-263, page 55.
11. Crane Company, Chicago, Illinois.
12. Analysis of Thermal and Pressure Stresses in Caliber .50 Light M. G. Barrel. L. M. K. Boelter et al., University of California. January 1945.

B. Brinell
V. Vickers
A. Approximate

Transformation Temperature in °C[1]

Gun Steels	Ac_1	Ac_3	Ar_3	Ar_1
SAE 4140	750	795	745	694
SAE 4150	742	757	735	694

2011

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TABLE III - NOMINAL COMPOSITION OF ALLOYS USED AS LINERS

Material	C	Mn	P max.	S max.	Si	Cr	Mo	Cu	Co	Ni	Al	Fe	W
Gun Steel:													
SAE 4140[1]	0.38–0.43	0.75–1.00	0.04	0.04	0.20–0.35	0.80–1.10	0.15–0.25	-	-	-	-	-	-
SAE 4150[2]	0.45–0.60	0.60–0.90	0.04	0.05	0.20–0.35	0.80–1.10	0.15–0.25	-	-	-	-	-	-
Silicon Steel[7];	-	-	-	-	4.7	-	-	-	-	-	-	-	-
SAE 9260[1]	0.55–0.65	0.70–0.90	0.04	0.04	1.80–2.20	-	-	-	-	-	-	-	-
Monel Metal[6]	0.3	2.0	-	-	S	-	-	28.5	-	67.5	0.5	0.5	-
Stellite:													
# 6[5]	0.50–0.70	-	-	-	-	29.0	-	-	66.0	-	-	-	4.5
#21[4]	0.25–0.35	S	-	-	S	27–30	5.2	-	60–65	-	-	S	-
#22[5]	1.0	S	-	-	1.5	27.0	-	-	65.0	-	-	1.5	4.0
"Z"-Nickel	Not stated by Maker.												

(1) Metals and Alloys Data Book - Hoyt, 1943.
(2) U.S. Army Specifications.
(3) Report of Resistant Materials Committee - January 1944, Appendix - p.59.
(4) Haynes-Stellite Company
(5) Crane Company
(6) Navy Department
(7) Carnegie Illinois Steel Company
(S) "Small Amount"

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B. CONTROL TESTS

1. Erosion of Gun Steel. In order that comparison can be made between the erosion shown by gun steel and that shown when liners and coatings are used, it is necessary to establish with some care just how the progress of erosion takes place in an unlined, uncoated barrel of gun steel. For this purpose, two firing tests, used as controls, were made under nearly identical conditions with each of three types of bullets, namely, Ball M-2, copper banded artillery (designated hereafter as A.T.), and pre-engraved (designated hereafter as P.E.)

The term erosion implies the gradual enlargement of the bore with the resulting loss in pressure and velocity, loss in range and increased accuracy dispersion. This increase in bore diameter may occur either by (1) chemical attack, (2) thermal effects (such as melting or softening) and/or (3) mechanical effects, such as swaging of the lands by the engraving stresses and abrasion by the bullet and powder.

(a) Erosion Resistant Properties of Gun Steel.

Although the physical properties (tensile strength, yield point, ductility, etc.) of the gun steels are very good, the thermal and chemical properties are not suitable to give good performance in a hyper-velocity gun.

The failure of gun steel may be attributed to:

(1) Low Melting Point - The high potential double base powders necessary for an efficient hyper-velocity gun produce bore surface temperatures in the vicinity of the melting point of the steel (1450°C).

(2) Thermal Transformation of the Steel Surface - A chemically and thermally altered layer is formed at the steel surface after one

rri

round. The depth of this altered layer is a function of the flame temperature of the powder gas. This altered layer is less resistant to erosion.

(3) Low hot hardness - Gun steel (SAE 4150) shows a sharp downward break in the hardness vs temperature and the yield point vs temperature curves. At the maximum temperature obtained by the bore surface a lowering of the hardness permits plastic deformation of the lands to occur under the engraving stresses.

(4) Poor resistance to chemical reaction - Since gun steel is essentially iron, we have to deal mainly with the chemistry of iron. At the temperatures attained in the gun the powder gases can react with the iron in the steel to form carbides, oxides, sulphides and nitrides.

The erosion of gun steel, irrespective of the powder and the bullet used, starts at the origin of rifling and advances toward the muzzle as the number of rounds increases.

It is characterized by:

(1) cracking of the bore surface

(2) "melting" or softening of the bore surface

(3) swaging of the lands

With double base powder a definite crack pattern can be seen after a few rounds. It has been shown that an altered layer forms during the first round fired and melting of the land corner is also observed after one round.

Swaging of gun steel is usually overshadowed by the effects of thermal erosion.

23-13

(b) Erosion Tests with Ball M-2 (BM-2), banded Artillery Type (A.T.) and Pre-Engraved (P.E.) bullets.

Two control tests for each type of bullet were fired using double base powder.

The increase in bore diameter, the loss in pressure and velocity and the round number for a loss in velocity of 200 fps. are tabulated in Table IV.

Table IV - Comparison of Change in Bore Dimensions and Ballistics

Test	Firing Schedule	Rds. Fired	P_o psi(Cu)	V_o fps	ΔP after psi	ΔV after fps	ΔL in.x10^{-3}	ΔG in.x10^{-3}	ΔV =-200 fps after-Rds.
E(F3)	I	115	58700	3710	- 8900	-290	14.6	7.7	49
E(F4)	I	115	62600	3720	-15800	-288	16.0	10.2	55
C(F6)	II	150	57700	3700	-15700	-315	23.8	11.8	90
C(F12)	II	150	57600	3700	-13500	-330	18.7	10.7	100
L1(F5)	II	290	57500	3700	- 7900	-284	25.8	19.6	215
L1(F9)	II	290	57500	3705	- 7800	-230	19.9	14.7	265

A comparison of the distribution of erosion along the bore surface is shown on Figures 7 and 8.

A comparison of the progress of erosion for the lands and grooves at 0.5 inch beyond the origin of rifling is shown Figures 9 and 10.

A comparison of the progress of velocity and pressure change is shown on Figures 11 and 12.

The above data shows that

(1) Consistent erosion results can be obtained when firing conditions are closely controlled.

(2) Pre-engraved bullets eliminate the wear factor due to engraving stresses. The erosion observed with P.E. bullets is approximately half of the erosion observed with BM-2 and A.T. bullets.

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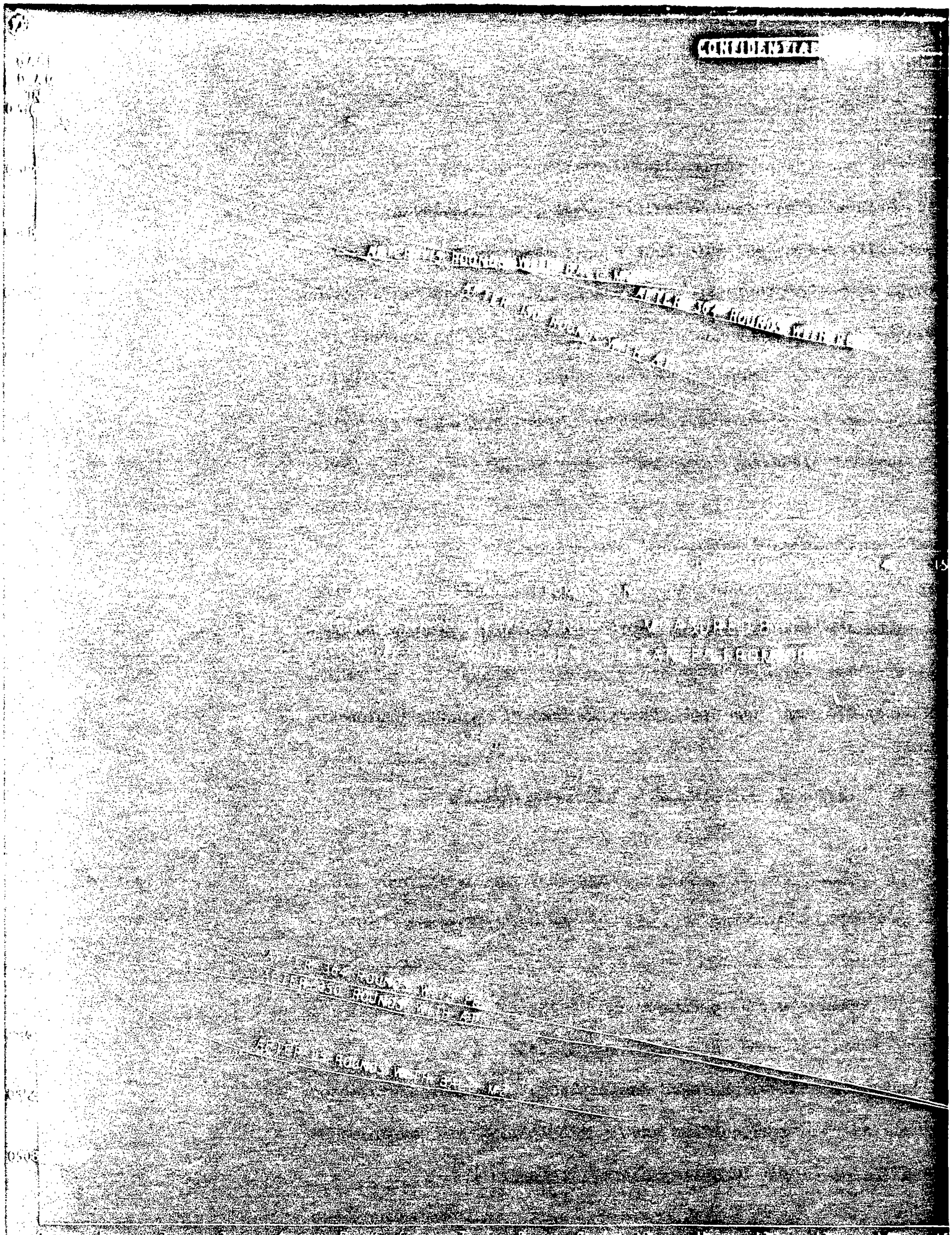

FIG ... DISTANCE FROM ORIGIN (IN.)

DISTRIBUTION OF EROSION OF GROOVES AS MEASURED BY

GAGE DIAMETER AT DIFFERENT DISTANCES FROM OR

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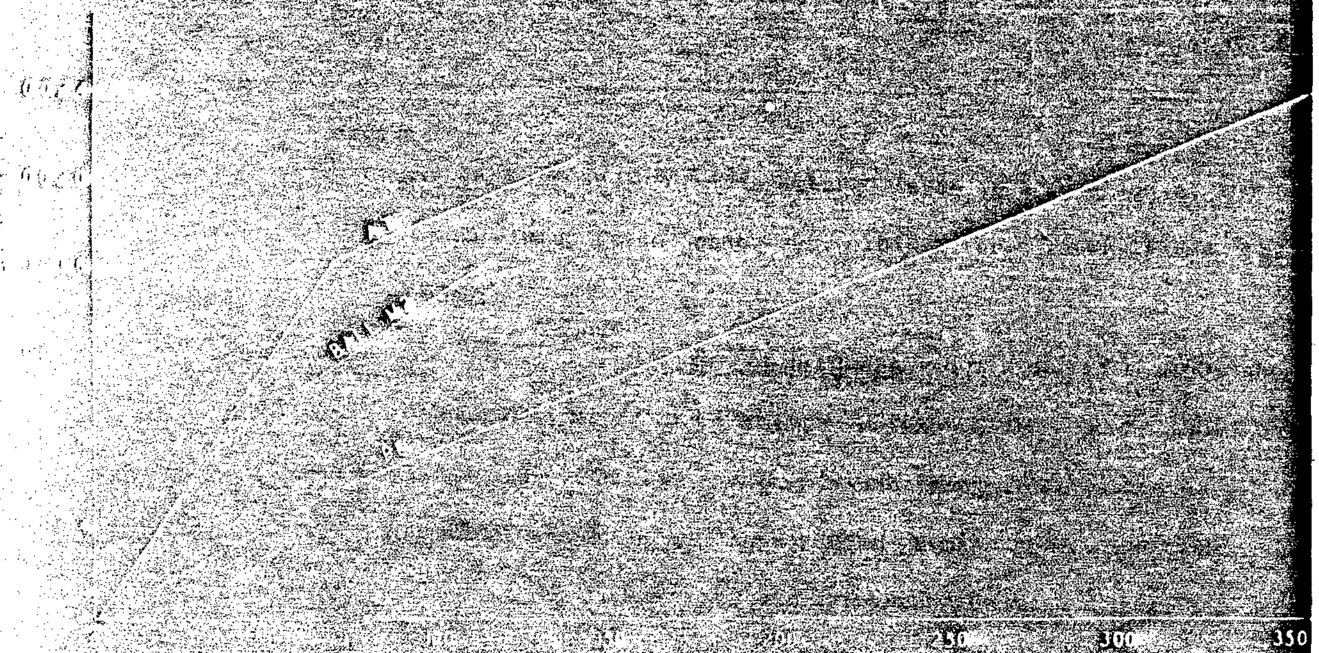


NUMBER OF ROUNDS

PROGRESS OF INCREASE IN LAND DIAMETER
AT 0.5" FROM OR VS NUMBER OF ROUNDS FIRED

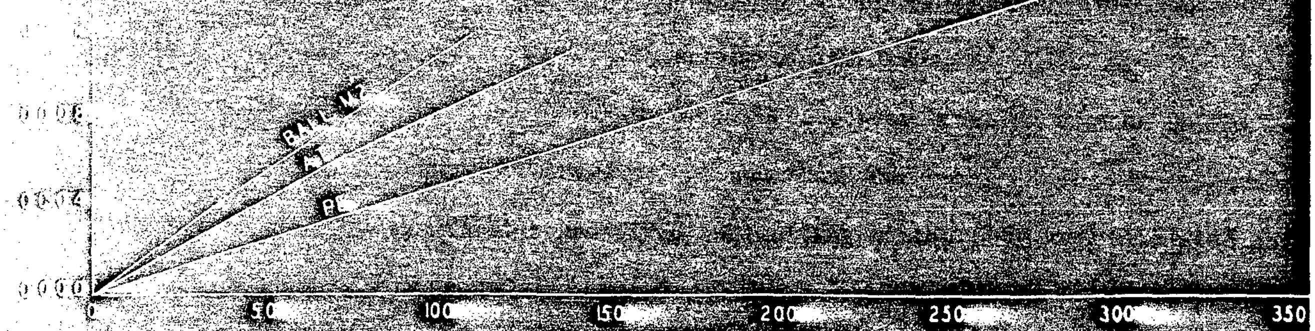


FIG 10 NUMBER OF ROUNDS

PROGRESS OF INCREASE IN GROOVE DIAMETER
AT 0.5" FROM OR VS NUMBER OF ROUNDS FIRED

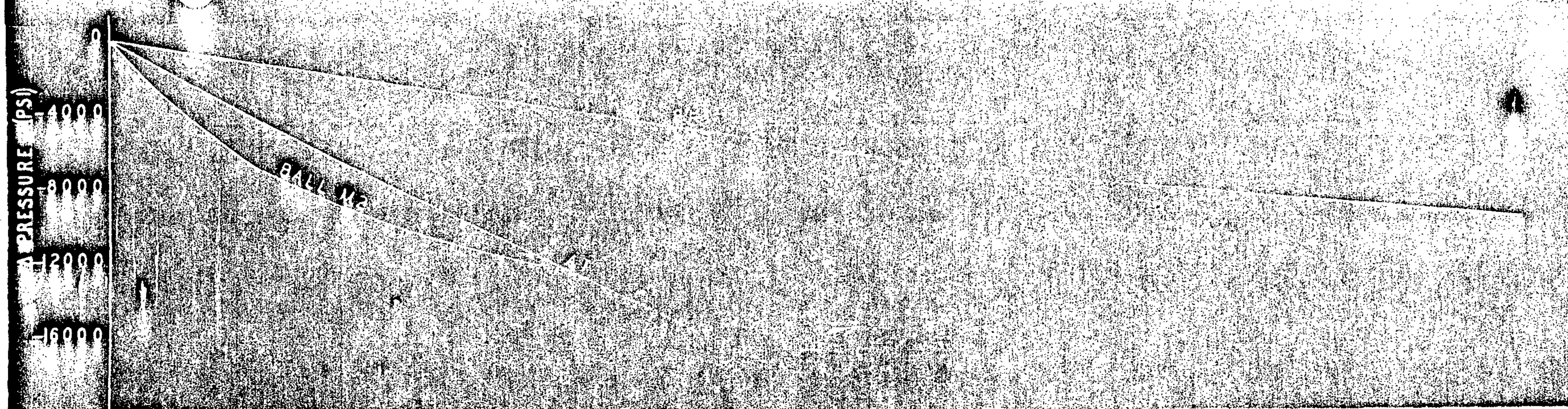
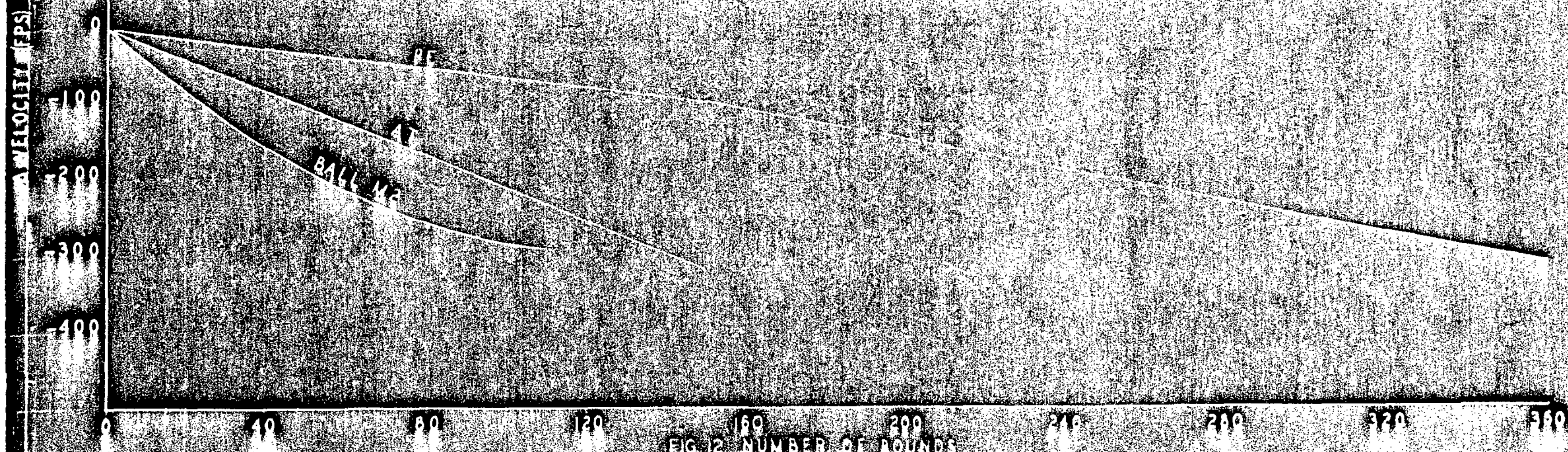


FIG 11 PRESSURE CHANGE VS NUMBER OF ROUNDS FIRED



VELOCITY CHANGE VS NUMBER OF ROUNDS FIRED

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(3) The progress of erosion curves show that the rates of erosion for Ball M-2 and A.T. bullets are the same for 35 rounds. After 35 rounds a sharp break occurs sooner in the curve for Ball M-2 bullets because the rifling is only .005" deep. With A.T. bullets the rifling is .010" and the break in the curve occurs after 70 rounds.

C. LINERS OF RESISTANT MATERIALS

1. Molybdenum and Molybdenum Alloys.

The molybdenum and molydbenum alloy liners described in this section were prepared by the Westinghouse Research Laboratories at East Pittsburgh, Pa. under Contract OEM-sr 915 from alloys made by the Westinghouse Lamp Division at Bloomfield, N. J. under Contract OEM-sr 1205. The details covering the manufacture and the properties of the various molybdenum liners submitted may be obtained from the Westinghouse report.

(a) Erosion Resistant Properties of Molybdenum and Molybdenum Alloys. The high melting point, better thermal conductivity and excellent chemical properties of molybdenum should produce liners that are very resistant to thermal and chemical attack by the powder gases. However, its method of manufacture from powder by powder metallurgy gives material that is poor in physical properties unless the material is given the proper work and heat treatment. Bars worked well in only one direction give a material that has good properties in only one direction.

Many of the early liners tested did not have sufficient working and consequently they failed after a few number of rounds by cracking and spalling of the metal from the surface. These early tests, however, showed the superior erosion resistant properties of molybdenum.

Low Hot Hardness. Molybdenum has been shown to be too soft at the temperatures reached in a gun to withstand the engraving stresses. Unless the Mo has been hardened the bore will enlarge because of the flattening of the lands and a drop in pressure and velocity will be observed even though the material is resistant to the powder gases.

Low Coefficient of Expansion. The thermal coefficient of expansion of molybdenum is less than half of the coefficient of expansion of gun steel. In long erosion bursts the liner has moved so that the rifling is out of line in cases where the interference-fit has not been great enough to hold the liner.

(1) Types of Failure. The types of failure observed in Mo liners may be attributed to

Low Strength and Ductility. This can be corrected by proper working and heat treatment to produce the proper strength and microstructure.

Low Hot Hardness. This can also be improved by alloying with Ni or Co and proper working and heat treatment.

Low Coefficient of Expansion. This can be corrected by insertion in the carrier under a high shrink-fit interference or assembly in a carrier of the proper coefficient of expansion so that support of the Mo liner is maintained at all temperatures.

The types of failure observed in Mo liners tested can be grouped as follows:

(a) Swaging of lands at O.R.

(b) Movement of the Liner.

(i) Forward movement of liner causing the joint beneath the cartridge case to open.

(ii) Plastic flow of metal ("ironing") toward the muzzle end of the liner causing a constriction at the end of the liner.

(iii) Warping of staves causing a constriction at the breech end.

(iv) Rotation of liner causing a missalignment of the rifling.

(v) Opening of the seams.

(c) Cracking of the Liner.

(i) Longitudinal cracking - this usually occurs in the center of the grooves.

(ii) Transverse cracking.

(iii) Surface checkerwork cracking caused by the thermal stresses at the bore surface.

(d) Scalling of the Metal.

(i) Along the edges of the seams.

(ii) At the land crossing of straight seams.

(iii) Emanating from tool marks on the surface.

(b) Erosion Tests on Molybdenum Liners.

(1) Variables Tested. The following variables were tested in the firing tests outlined below:

(a) Composition

(b) Smooth bore and rifled liners

(c) Seamless and multi-stave liners

(d) Straight and helical twisted liners

(e) Precision twisted liners

(f) Liners with and without shoulder

(g) Varying interference between liner and carrier

(h) Liners with and without body taper

One of the most important variables which was hard to control was the microstructure of the material. The program has now reached a point where material having good microstructure can be consistently produced.

(2) Firing Schedules. The superior erosion resistant properties of Mo made necessary the use of a more severe erosion schedule. Schedules III and IV were used on the last group of molybdenum liners. The properties of the molybdenum have been improved in the last liners tested, so that the most severe firing schedule IV has now been adopted as standard for superior erosion resistant liners. These schedules are as follows:

Schedule III

10 rounds Velocity & Pressure
130 rounds Erosion at 6 R.P.M. } Group I

After examination and gage measurement the process was repeated to failure.

Schedule IV

10 rounds Velocity & Pressure 90 rounds Erosion at 10 to 16 R.P.M.	)	Group I
10 rounds Velocity & Pressure 190 rounds Erosion at 10 to 16 R.P.M.	)	Group II
10 rounds Velocity & Pressure 290 rounds Erosion at 10 to 16 R.P.M.	)	Group III
10 rounds Velocity & Pressure 280 rounds Erosion at 10 to 16 R.P.M. 10 rounds Velocity & Pressure	)	Group IV

(3) Barrel Temperature Measurements. Temperature measurements were made by attaching iron-constantan thermocouples on the outside of the barrel at 10-1/2" from the breech. The thermocouples were peened in the steel surface according to the procedure described in the Leeds & Northrup Report under Contract OEM-sr 536.

The barrel temperatures reached in each of the firing schedules are as follows:

Schedule	Temp. after	20	55	90	130	190	280	290 rds.
I		95°C	-	-	-	-	-	-
II		-	185°C	-	-	-	-	-
III		-	-	-	330°C	-	-	-
IV		-	-	284°C	-	416°C	500°C	502°C

(4) Summary of Results. Table V gives a chronological list of the molybdenum liners tested in this program. Tests prior to firing test E(F33) were made on Mo material that had inferior microstructure and hence inferior physical properties. The details of each firing test are given in the Appendix. A summary of the results of

33-15

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TABLE V - SUMMARY OF FIRING TESTS ON MOLYBDENUM LINERS

F = Failure   S = Satisfactory

Test	Compositon	Bore	Bullet	Powder	Rds. Fired	Swaging	Constriction	Cracking of Liner Long.	Cracking of Liner Transverse	Spalling	Gas Erosion
E(F5)	Mo	Rifled	B.M2	D.B.	24	S	S	F	F	S	S
E(F6)	Mo	Rifled	B.M2	IMR	1	S	S	F	F	S	S
E(F7)	Mo	Smooth	B.M2	D.B.	5	-	-	F	F	F	S
E(F10)	Mo	Smooth	B.M2	IMR	9	-	-	F	S	S	S
E(F11)	Mo	Smooth	B.M2	D.B.	46	-	-	F	S	F	S
E(F12)	Mo	Smooth 2-Staves	B.M2	D.B.	150	-	-	F	F	F	S
E(F16)	Mo	Rifled 10-Staves	B.M2	D.B.	150	F	S	S	S	S	S
E(F17)	Mo	Smooth 10-Staves	B.M2	D.B.	150	-	-	S	S	S	S
E(F18)	Mo	Rifled 2-Staves	B.M2	D.B.	70	S	S	F	F	F	S
E(F19)	Mo	Rifled 2-Staves	P.E.	D.B.	150	S	S	S	S	S	S
E(F21)	Mo	Incast	B.M2	D.B.	10	S	S	F	F	F	S
E(F24)	90 Mo-10 W	Rifled 2 Staves	B.M2	D.B.	150	F	S	F	F	F	S
E(F25)	85 Mo-15 W	Rifled 2-Staves	B.M2	D.B.	148	S	S	F	F	F	S
E(F28)	80 Mo-20 W	Rifled 2-Staves	B.M2	D.B.	72	-	-	F	F	F	S
E(F35)	Mo	Rifled 2-Staves	P.E.	D.B.	454	F	S	S	S	F	S
E(F36)	Mo + .05 Ni	Rifled 2-Staves	B.M2	D.B.	309	F	F	F	F	[illegible]	S
E(F38)	Mo + .01 Ni	Rifled 2-Staves	B.M2	40% D.B.	119	F	F	F	S	S	S
E(F39)	Mo	Rifled 2-Staves	P.E.	40% D.B.	294	F	F	F	S	F	S

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24-12

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TABLE V (Continued)

Test	Composition	Bore	Bullet	Powder	Rds. Fired	Swaging	Constriction	Cracking of Liner Long.	Cracking of Liner Transverse	Spalling	Gas Erosion
E(F40)	Mo + 15 W	Rifled 2-Staves	P.E.	40% D.B.	146	F	F	F	F	S	S
E(F41)	Mo + 15 W	Rifled 2-Staves	B.M2	D.B.	432	F	F	F	F	S	S
E(F42)	Mo + .01 Ni	Rifled 2-Staves	B.M2	D.B.	148	S	F	F	S	F	S
E(F43)	Mo + .01 Ni	Rifled 4-Staves	B.M2	D.B.	155	F	F	F	S	F	S
E(F44)	Mo + .08 Ni	Rifled 2-Staves	B.M2	D.B.	166	S	S	F	S	F	S
E(F45)	Mo + .1 Ni	Rifled 4-Staves	B.M2	D.B.	293	F	S	F	S	F	S
E(F47)	Mo + .1 Co	Rifled 2-Staves	B.M2	D.B.	1133	F	F	F	S	F	S
E(F48)	Mo + .1 Co	Rifled 2-Staves	B.M2	D.B.	152	S	F	F	S	F	S
E(F49)	Mo + .1 Co	Rifled 2-Staves	B.M2	D.B.	2022	F	S	F	S	F	S
E(F50)	Mo + .1 Co	Rifled 2-Staves	B.M2	D.B.	2024	F	S	F	S	F	S
E(F51)	Mo + .1 Co	Rifled 2-Staves	P.E.	D.B.	442	F	F	F	S	F	S
E(F53)	Mo + .1 Co	Rifled 2-Staves	P.E.	D.B.	1052	S	S	F	S	F	S
E(F54)	Mo + .1 Co	Rifled 2-Staves	P.E.	D.B.	4	Failed due to unsupported area.					
E(F55)	Mo + .1 Co	Rifled 2-Staves	B.M2	D.B.	77	F	F	F	S	F	S
E(F56)	Mo	Rifled 2-Staves	B.M2	D.B.	905	F	S	F	S	F	S
E(F57)	Mo + .1 Co	Rifled 2-Stave	B.M2	D.B.	785	F	F	F	F	F	S

CONFIDENTIAL

35-13

the variables tested is as follows:

(a) Smooth bore liners: The first Mo liners tested had inferior physical properties and failed in the first few rounds fired. Smooth bore liners were tested to eliminate the machine work of rifling until material of satisfactory strength and ductility could be produced.

Five smooth bore liners were tested (E-F7, E-F10, E-F11, E-F12).

(b) Seamless and multi-stave liners: The first five Mo liners tested (E-F5, E-F6, E-F7, E-F10 and E-F11) were drilled from swaged bars. These liners failed badly by longitudinal cracking because of inferior physical properties.

All liners tested since these have been made in the form of staves. The stave liners permitted the use of molybdenum having lower strength and ductility. As these properties are improved it may be possible to use seamless liners.

Two-stave, four-stave and ten-stave liners have been tested. In the Caliber .50 gun there has been no advantage in making a liner with more than two staves. A theoretical discussion of the stresses in multi-stave liners is given in Armor and Ordnance Report A-273 by Brace and Marden.

(c) Straight and helical twisted liners: In a multi-stave liner with straight seams, the seams between the staves cross the lands. There has been serious spalling and tearing of the metal at these land-seam crossings due to the impact of the bullet on material of low strength and ductility. As the material has been improved the extent of failure at the land-seam crossings has been reduced. However, it can be stated that a helical twisted two-stave liner made with molybdenum having the best physical properties produced today, is in better condition than a straight two-stave liner after being fired the same number of rounds.

A comparison of straight and helical twisted liners is shown in Tests E(F47) and E(F49) fired 1133 and 2022 rounds respectively. (See Appendix-pages 111 and 112.)

(d) Effect of integral shoulder. Tests E(F33), E(F36), E(F39) and E(F57) were made on liners without an integral shoulder. All liners tested to date made without an integral shoulder that were fired on Schedules III and IV have moved forward and produced an opening at the rear joint beneath the cartridge case. Extrusion of the brass case into this opening prevented extraction of the case and stopped the test.

The results of these tests show that a liner with an integral shoulder is necessary for the best performance, using the best Mo that is now available. (See Appendix-pages 108, 107 and 117).

(e) Precision twisting of staves. The staves in Tests E(F42), E(F45), E(F54) and E(F55) were precision twisted by the Westinghouse Research Laboratories at East Pittsburgh. The other twisted liners were hot twisted at Bloomfield and then machined to size.

The results of the test show that with good material there is no advantage in performance with a precision twisted liner.

(f) Varying interference between liner and carrier. All liners tested had interference between the liner and the carrier. This interference varied from 0.0015" to 0.004" on the diameter.

The tests showed the best performance is obtained with the greatest interference. It is necessary to cool the liner and heat the carrier when there is insertion interference of .003" and .004".

(g) Liners with and without body taper. One liner was inserted in the carrier without any body taper and fired 2024 rounds in Test E(F50). Compared with its companion test E(F49), which was fired 2022 rounds, the taper did not affect the performance. Body taper, however, makes the liner insertion easier. (See Appendix - pages 112 and 114).

(h) Composition. Pure molybdenum has been shown to be too soft to withstand engraving stresses. The addition of small amounts of nickel and cobalt and 15% tungsten improve the strength and hardness with the same amount of forging (hot working). A comparison of the effects produced by the addition of these metals is shown in the following table. The advance of the 0.505" land gage gives a good measurement of the extent of swaging of the lands.

Test	Composition	Advance of 0.505" Gage after 300 rds.
E(F56)	Mo (pure)	+ 1.02"
E(F45)	Mo + 0.01% Ni	+ 0.07
E(F36)	Mo + 0.05% Ni	+ 0.99
E(F47)	Mo + 0.1 % Co	+ 0.05
E(F49)	Mo + 0.1 % Co	+ 0.03
E(F50)	Mo + 0.1 % Co	+ 0.07
E(F41)	Mo + 15% W	+ 0.24

These results have shown the composition with 0.1% Co to give the best and most consistent performance.

The superior erosion resistant properties of molybdenum are clearly shown in the following tables and curves.

Tables VI and VII compare the erosion resistance of Mo and gun steel.

The groove gage measurements are taken as being more representative of resistance to gas erosion.

TABLE VI - COMPARISON OF ADVANCE OF GROOVE GAGES

Gage Dia.	1 Gun Steel After 115 Rds.	2 Gun Steel After 70 Rds.	3 Molybdenum After 294 Rds.	4 Mo + 0.1% Co After 2022 Rds.
0.513	+ 6.87"	-	+ 0.05"	+ 0.16"
0.515	+ 4.25	-	+ 0.07	+ 0.14
0.517	+ 2.37	+ 6.00"	+ 0.07	+ 0.09
0.519	+ 1.45	+ 5.29	+ 0.07	+ 0.03
0.521	+ 0.88	+ 4.75	+ 0.07	+ 0.01

Column 1 - Using 20% NG powder and Ball M-2 Bullets
Column 2 - Using 40% NG powder and Ball M-2 Bullets
Column 3 - Using 40% NG powder and Ball M-2 Bullets
Column 4 - Using 20% NG powder and Ball M-2 Bullets

Figure 13 compares the profile of the grooves of gun steel liners fired (a) 70 rounds with 40% nitroglycerin powder, (b) 115 rounds with 20% nitroglycerin powder and molybdenum liners fired (a) 294 rounds with 40% nitroglycerin powder and (b) 2022 rounds with 20% nitroglycerin powder. These data show the absence of any powder gas erosion of the molybdenum surface even with the highly erosive 40% nitroglycerin powder.

The land gage measurements in Table VII show the extent of swaging of the molybdenum.

FIG.13 - EROSION RESISTANCE OF MOLYBDENUM
ADVANCE OF GROOVE GAGES

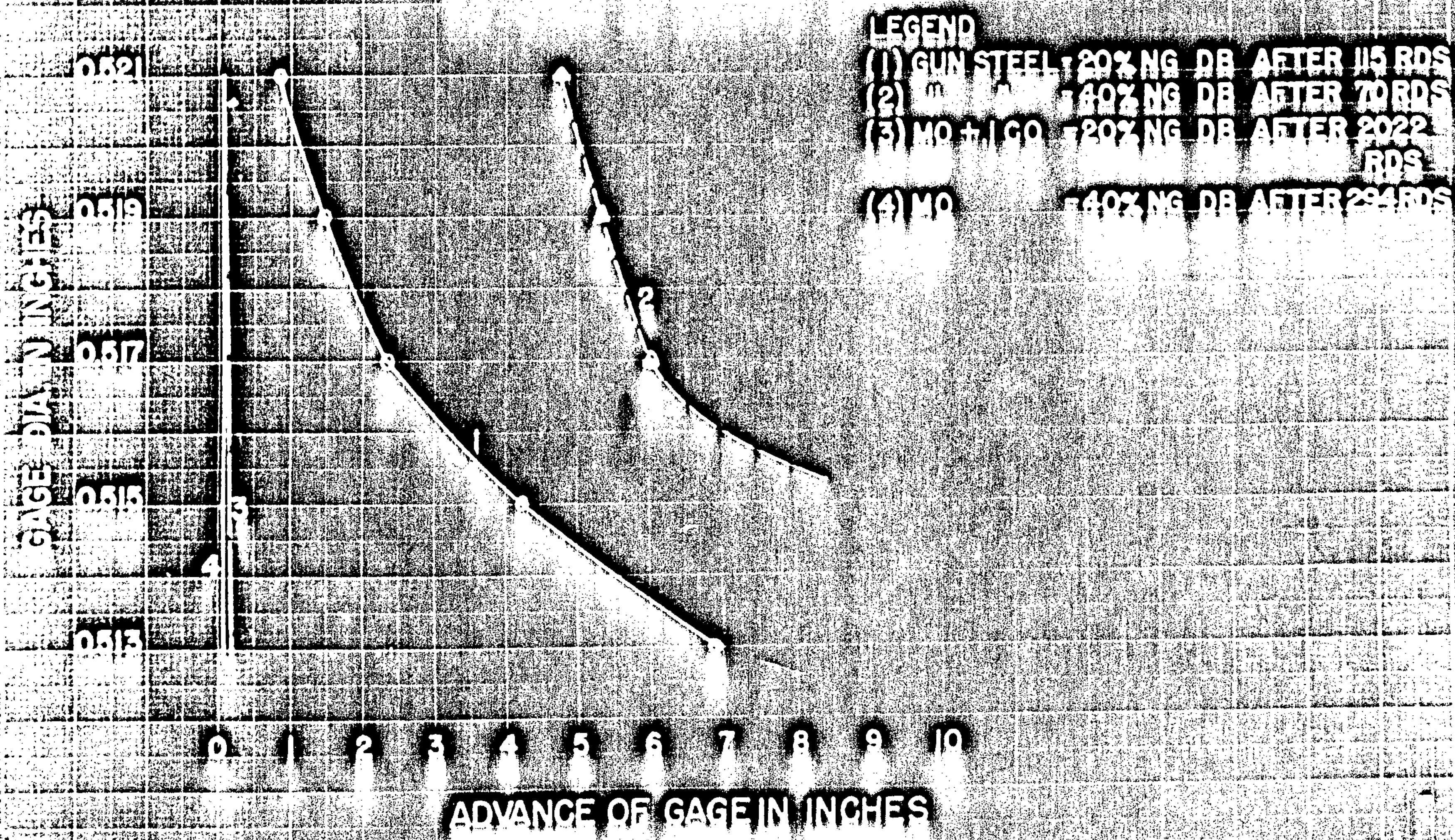


TABLE VII - COMPARISON OF ADVANCE OF LAND GAGES

Gage Dia.	Gun Steel After 115 Rds. 20% NG Powder	Mo + 0.1% Co After 2022 Rds. 20% NG Powder
0.501	+ 18.7"	+ 5.73"
0.503	+ 14.5	+ 2.96
0.505	+ 11.3	+ 2.15
0.507	+ 9.0	+ 0.17
0.509	+ 6.6	- 0.04
0.511	+ 3.9	- 0.15

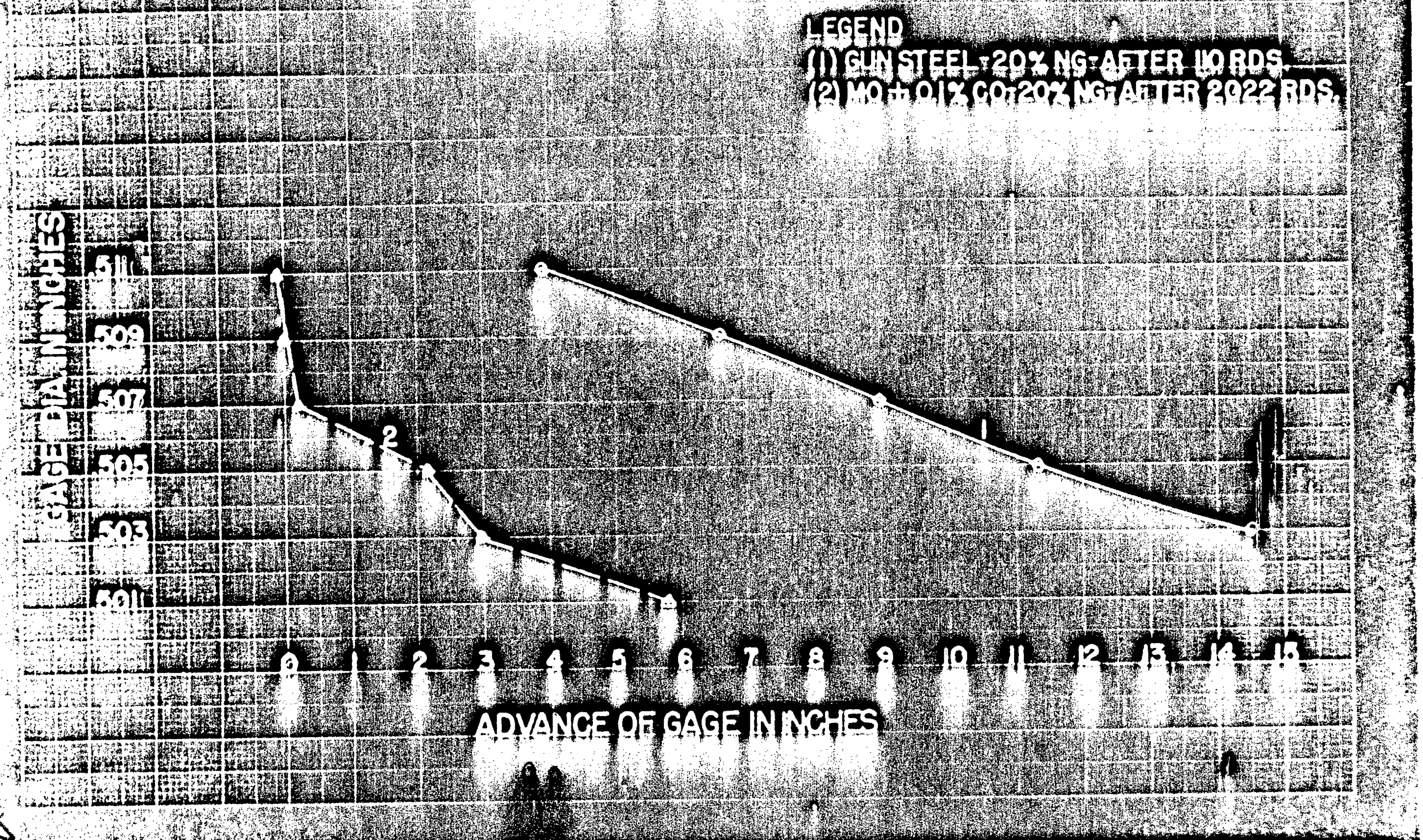
Figure 14 compares the profile of the lands of a gun steel liner fired 115 rounds with 20% nitroglycerin powder and a molybdenum liner fired 2022 rounds with 20% nitroglycerin powder. Since the groove gages showed no powder gas erosion, the change in the land profile of the molybdenum liner is due entirely to the swaging action of the bullet.

A comparison of the pressure change with gun steel liner is shown on Figure 15. During the test of E(F49) the molybdenum liner outlasted three new chrome plated muzzle sections.

A summary of the results of all the molybdenum liners tested after Test E(F33) is given in Table VIII.

(5) Metallographic Examination. Sections of some of the fired liners were sent to Harvard University for metallographic examination. The results of these examinations may be obtained from the Harvard Report on "Metallographic Examination of Gun Liners and Coatings Tested under Hypervelocity Conditions".

FIG.14-EROSION RESISTANCE OF MOLYBDENUM
ADVANCE OF LAND GAGES



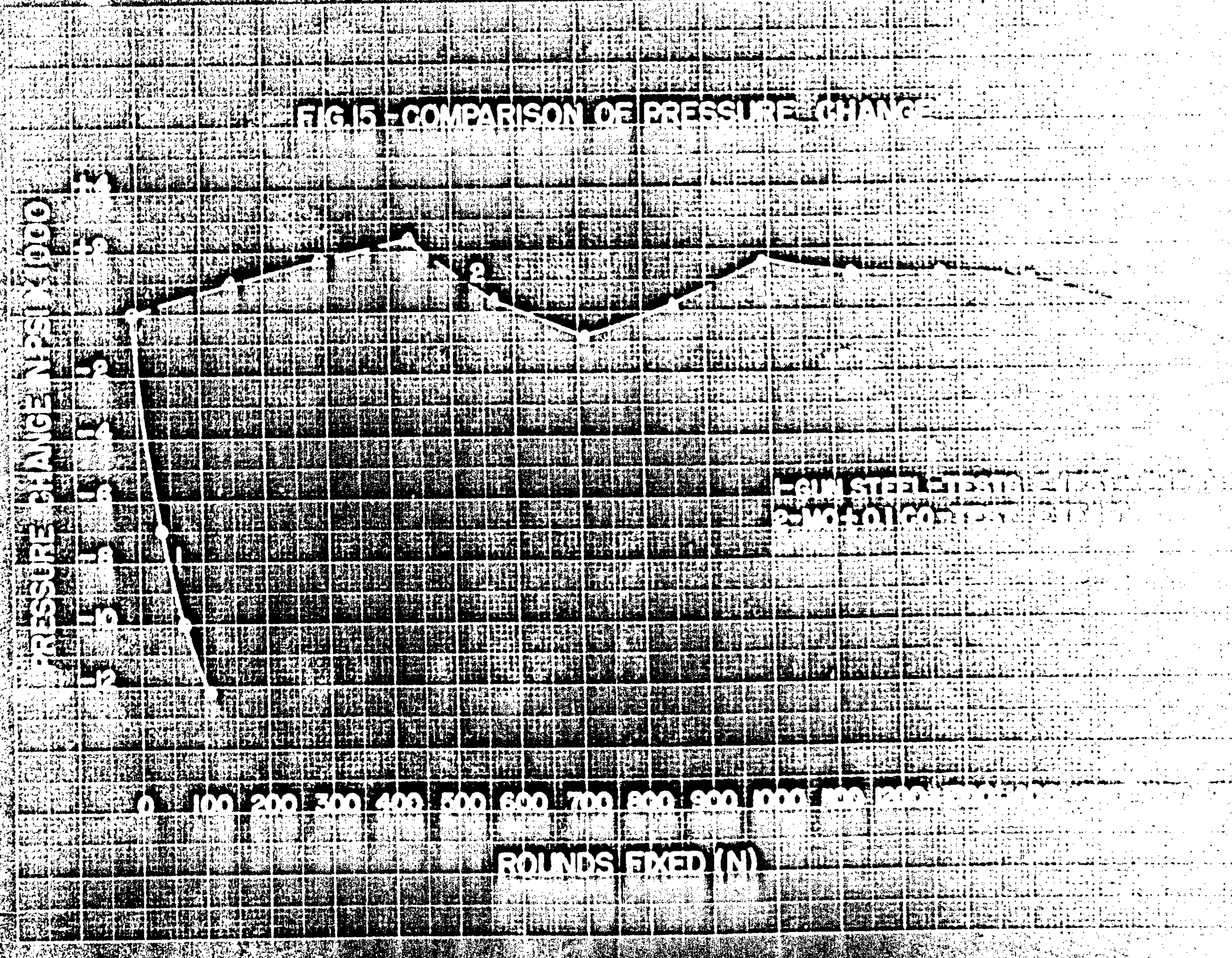


FIG.15 - COMPARISON OF PRESSURE CHANGE

(6) Conclusions

The results obtained in testing the Molybdenum liners show:

(a) Molybdenum is completely resistant to powder gas attack. There was no erosion after 294 rounds with a double base powder containing 40% nitroglycerin, or after 2024 rounds with a double base powder containing 20% nitroglycerin.

(b) The failures observed in the Mo metal now being produced are (1) Longitudinal cracking, (2) Spalling, and (3) Swaging of the lands at the origin of rifling.

(c) With the present Mo metal the following composition and design characteristics have given the best results in a liner for maximum performance under hypervelocity conditions:

1. Composition - Molybdenum + 0.1% Cobalt.
2. Two-Staves - Helical Seams - Hot twisted.
3. Shoulder - 0.830" to 0.840" O.D. with 1/32" face and 3/4" length.
4. Body of Liner - 0.770" to 0.780" O.D. - 7-3/8" length with taper 1/32 in/ft. on diameter.
5. Inserted in Standard Carrier (See Fig. 4) with 0.003" interference on the diameter.

TABLE VIII - SUMMARY OF MO LINER TESTS

(A) Method of Assembly

Test	Liner	Composition	Construction: Staves	Seam (1)	Shoulder (2)	Twist (3)	Body (4)	Insertion (5) Interference
E-35	W-14	Mo	2	Straight	None	None	1/32"	-
E-36	W-15	Mo + .05 Ni	2	Helical	None	H-B	1/32" x .675"	.0015" (CP)
E-38	W-16-1	Mo + .01 Ni	2	H	None	H-B	1/32" x .720"	.0015" (CP)
E-39	W-17	Mo	2	H	None	H-B	1/32" x .722"	.0015" (CP)
E-40	W-18-1	Mo + 15 W	2	H	3/4" x 1/32"	H-B	1/32"	>.0015" (CP)
E-41	W-18-2	Mo + 15 W	2	H	3/4" x 1/32"	H-B	1/32"	>.003" (CP)
E-42	W-16-2	Mo + .01 Ni	2	H	3/4" x 1/32"	P-P	1/32" x .720"	.0015" (CP)
E-43	W-16-3	Mo + .01 Ni	4	S	3/4" x 1/32" x .790"	None	1/32" x .726"	.0015" (CP)
E-44	BL-25	Mo + .08 Ni	2	H	3/4" x 1/32" x .763"	H-B	1/32" x .725"	.0015" (CP)
E-45	W-16-4	Mo + .01 Ni	4	H	3/4" x 1/32" x .739"	P-P	1/32" x .724"	.002" (CP)
E-48	BL-33-3	Mo + 0.1 Co	2	S	3/4" x 1/32" x .820"	None	1/32" x .773"	.003" (SF)
E-47	BL-33-4	Mo + 0.1 Co	2	S	3/4" x 1/32" x .821"	None	1/32" x .775"	.003" (SF)
E-49	BL-33-5	Mo + 0.1 Co	2	H	3/4" x 1/32" x .834"	H-B	1/32" x .775"	.003" (SF)
E-50	BL-33-7	Mo + 0.1 Co	2	H	3/4" x 1/32" x .834"	H-B	0 x .784"	.004" (SF)
E-51	BL-36-1	Mo + 0.1 Co	2	S	3/4" x 1/32" x .844"	None	1/32" x .776"	.003" (SF)
E-53	BL-37-1	Mo + 0.1 Co	2	H	3/4" x .0185 x .810"	H-B	1/32" x .775"	.003" (SF)
E-54	BL-36-2	Mo + 0.1 Co	2	H	3/4" x 1/32" x .838"	P-P	1/32" x .776"	.003" (SF)
E-55	BL-35	Mo + 0.1 Co	2	H	3/4" x 1/32" x .843"	P-P	1/32" x .773"	.003" (SF)
E-56	BL-38	Mo	2	H	3/4" x 1/32" x .838"	H-B	1/32" x .774"	.003" (SF)
E-57	BL-39-1	Mo + 0.1 Co	2	H	None	H-B	1/32" x .774"	.003" (SF)

(1) Seams - (a) Helical - follow in grooves; (b) Straight - cross land.
(2) Shoulder - Length x Face x Diameter
(3) Twist - (a) H-B - Hot twisted at Bloomfield; (b) P-P - Precision twisted at Pittsburgh.
(4) Body - Taper in Inches/ft. x Max. O. D.
(5) Insertion - (a) CP - Cold Press; (b) SF - Shrink Fit.

45-13

CONFIDENTIAL

(B) Firing Conditions

Test	Liner	Powder	Grains	Bullet	Land Diameter	Groove Diameter	Pressure-psi(Cu)	Velocity-(fps)	Rounds Fired
E-35	W-14	D.B. 20% N.G.	476	P.E. - Steel	0.4910"	0.5101"	58000	3615	454
E-36	W-15	"	476	Ball M2	0.5017	0.5121	57100	3700	309
E-38	W-16-1	D.B. 40% N.G.	372	"	0.5016	0.5132	59200	3350	119
E-39	W-17	"	365	P.E. - Steel	0.4917	0.5116	57900	3810	294
E-40	W-18-1	"	365	"	0.4924	0.5111	58900	3560	146
E-41	W-18-2	D.B. 20% N.G.	476	Ball M2	0.5010	0.5089	56800	3700	432
E-42	W-16-2	"	476	"	0.5012	0.5124	57600	3700	148
E-43	W-16-3	"	476	"	0.5013	0.5120	57200	3700	155
E-44	BL-23	"	476	"	0.5027	0.5128	55300	3675	186
E-45	W-16-4	"	476	"	0.5021	0.5138	57000	3700	293
E-46	BL-33-3	"	476	"	0.5014	0.5165	55100	-	152
E-47	BL-33-4	"	476	Ball M2-Cad.Plated	0.5015	0.5112	58400	3680	1133
E-49	BL-33-5	"	476	Ball M2	0.5010	0.5111	55600	-	2022
E-50	BL-33-7	"	476	"	0.5017	0.5162	56600	-	2024
E-51	BL-36-1	"	476	P.E. Parco-Lub.	0.4909	0.5105	57300	3695	442
E-53	BL-37-1	"	476	"	0.4931	0.5122	57000	3635	1052
E-54	BL-36-2	"	476	"	0.4910	0.5113	56500	-	4
E-55	BL-35	"	476	Ball M-2	0.5045	0.5144	58200	-	77
E-56	BL-38	"	476	"	0.5019	0.5114	55700	-	905
E-57	BL-39-1	"	476	"	0.5003	0.5111	58400	-	785

CONFIDENTIAL

46-13

CONFIDENTIAL

(C) Performance of Liner

Test	Liner	Gas Erosion	Swaging of Land at O.R. Advance of 0.505" gage-0.500" bore	Longitudinal Groove Cracking	Transverse Cracking	Movement of Liner	Seams
E-35	W-14	None	-0.05"	Slight	None	None	Spalling of metal where seams cross lands.
E-36	W-15	"	+0.99"	Slight in all grooves	None	Liner twisted - rifling out of line. Rear joint opened up. Constriction at muzzle end of liner.	Satisfactory
E-38	W-16-1	"	+0.12"	In all grooves	None	Rear joint opened up - Constriction at muzzle end of liner.	Satisfactory
E-39	W-17	"	+0.28"(1)	In all grooves	None	Rear joint opened up - Constriction at muzzle end of liner.	Satisfactory
E-40	W-18-1	"	+0.10"(1)	In all grooves	5 cracks ahead of shoulder	Rear joint tight. Staves opened up at transverse cracks - Constriction at muzzle end	Satisfactory
E-41	W-18-2	"	+0.90"	In all grooves	Cracking ahead of shoulder	Rear joint tight. Staves opened up at transverse cracks. Constriction at muzzle end.	Satisfactory
E-42	W-16-2	"	Liner broke up due to brittle condition.				

CONFIDENTIAL

47-13

CONFIDENTIAL

(C) Performance of Liner (Continued)

Test	Liner	Gas Erosion	Swaging of Land at O.R. Advance of 0.505" gage-0.500" bore	Longitudinal Groove Cracking	Transverse Cracking	Movement of Liner	Seams
E-43	W-16-3	None	+0.04"	In all grooves	None	Rear joint tight. Constriction at muzzle end of liner.	Spalling of metal where seams cross lands.
E-44	BL-25	"	-0.01"	In all grooves	Cracking at end of shoulder.	Rear joint tight. Liner twisted, rifling out of line. No constriction at muzzle end.	Satisfactory
E-45	W-16-4	"	+0.07"	In all grooves	None	Rear joint tight. Surface spalling of one stave at bullet seat. No constriction at muzzle end.	Satisfactory
E-47	BL-33-4	"	+0.60"	Pronounced in all grooves.	None	Constriction from 3" beyond O.R. to end of liner.	Satisfactory
E-48	BL-33-3	"	+0.03"	Slight	Slight at 1-1/2" beyond O.R.	Slight constriction at forward joint.	Severe spalling of metal where seams cross lands.
E-49	BL-33-5	"	+2.15"	Slight in all grooves.	At O.R.	No constriction.	Considerable spalling along seam.
E-50	BL-33-7	"	+1.86"	Slight	None	No constriction.	Satisfactory
E-51	BL-38-1	"	+1.39"(1)	Slight	None	No constriction. Rear joint opened only slightly.	Severe surface spalling along edge of seams.

CONFIDENTIAL

(C) Performance of Liner (Continued)

Test	Liner	Gas Erosion	Swaging of Land at O.R. Advance of 0.505" gage-0.500" bore	Longitudinal Groove Cracking	Transverse Cracking	Movement of Liner	Seams
E-53	BL-37-1	None	+0.04"(1)	Slight	None	Rear joint opened slightly.	Severe spalling along edge of seam at 4" to 8" beyond O.R.
E-54	BL-36-2	"	—	—	—	Failure in 4 Rds. due to unsupported area at shoulder.	—
E-55	BL-35	"	-0.02"	Slight	None	Constriction at the joint.	Satisfactory
E-56	BL-38	"	+5.72"	Moderate	None	No constriction - Joint opened only slightly.	Severe spalling along edge of seam at 5" to 8" beyond O.R.
E-57	BL-39-1	"	+0.23"	Severe	Severe	Constriction at muzzle end - Rear joint opened up.	Severe spalling along seams.

(1) Advance of 0.496" gage - 0.490" bore.

49.13

2. Chrome Base Alloys.

The chrome base alloy liners described in this section were prepared by The Climax Molybdenum Company under Contract OEMsr 1273. The details covering the methods of manufacture and properties of the various liners submitted may be obtained from the Climax Molybdenum report.

(a) Erosion Resistant Properties of the Chrome Base Alloys. Chromium has a melting point that is high enough to resist melting in the bore of a gun and is also chemically resistant to the powder gases. Erosion vent plug tests (1) have shown this metal to be one of the few metals that is resistant to powder gas attack. However, the physical properties of solid chromium are very poor in that it is very brittle. The object of the chrome base alloy program has been to find some alloying agents that would still retain the erosion resistant properties of chromium and at the same time impart ductility and strength to the resulting chromium alloy.

In the liners tested iron, tungsten and molybdenum have been added to chromium in varying percentages.

(1) Types of Failure Observed. In general the types of failure observed in the testing of these liners may be attributed to

Low Ductility. The longitudinal cracking observed in all the liners tested is due to the inherent low ductility contributed by the high percentage of chromium in the alloy.

Large Grain Size. Severe checkerwork cracking is observed, caused by the thermal stresses set up on the bore surface. These cracks usually follow the grain boundaries and because of the

50-13

brittleness and large grain size of the alloy, isolated blocks of the alloy are torn from the surface thereby producing a severely pitted appearance.

The types of failures observed are as follows:

(a) Longitudinal cracking of the liner.

(b) Transverse cracking of the liner - observed only in Test E(F58).

(c) Pitting of the surface.

(d) Volume change producing a constricted bore thereby resulting in excessive powder pressures.

(e) Slight erosion of the bore surface - only in the liner containing 45% iron.

(b) Erosion Tests on Chrome Base Alloys.

(1) Variables Tested. The following variables were tested in the firing tests outlined below:

(a) Composition

(b) Method of supporting liner in carrier

(c) Two-stave - Straight-seam liner

(2) Summary of Results. Table IX gives a chronological list of the chrome base alloy liners tested in this program. The details of each firing test are given in the Appendix, page 118.

The best composition tested to date is 60% chromium, 25% iron and 15% molybdenum. This composition is resistant to powder gas attack and is also hard enough to resist swaging at the temperatures reached in the gun.

51-13

TABLE IX - SUMMARY OF FIRING TESTS ON CHROME BASE ALLOY LINERS

F = Failure S = Satisfactory

Test	Liner	Composition	Bullet	Powder	Rds. Fired	Swaging	Cracking of Liner Long.	Cracking of Liner Transverse	Constriction	Pitting of Surface	Gas Erosion
E(F29)	CX-5	60 Cr + 25 Fe + 15 W	B.M2	D.B.	85	S	F	S	F	F	S
E(F30)	CX-6	50 Cr + 45 Fe + 5 Mo	B.M2	D.B.	84	-*	F	S	S	F	F
E(F31)	CX-10	60 Cr + 25 Fe + 15 Mo	B.M2	D.B.	309	S	F	S	S	F	S
E(F46)	CX-30	60 Cr + 30 Fe + 10 Mo	B.M2	D.B.	151	S	F	S	S	F	S
E(F52)	CX-34	60 Cr + 25 Fe + 15 Mo	B.M2	D.B.	568	S	F	S	F	F	S
E(F58)	CS-35	60 Cr + 25 Fe + 15 Mo	B.M2	D.B.	110	S	F	F	S	F	S

* Slight melting at O.R.

57-13

The results of all the liners tested may be summarized by stating that they all failed due to cracking: longitudinal, transverse and surface cracking.

The method of inserting the liner within another chrome base alloy liner so that the inner liner is under high compressive stresses failed to prevent the longitudinal cracking.

One liner was made in the form of 2 staves (Test E-F58) in an attempt to reduce the longitudinal cracking. Results showed the 2 stave liner did not reduce longitudinal cracking and that transverse cracking appeared. This is the only liner in the chrome base series that showed transverse cracking.

The test data on all these liners, however, show the chrome base alloys to be superior to gun steel and stellite #21, but inferior to molybdenum.

(3) Metallographic Examination. Sections of the fired liners were sent to Harvard University for metallographic examination. The results of these examinations may be obtained from the Harvard report on "Metallographic Examination of Gun Liners and Coatings Tested under Hyper-velocity Conditions".

(4) Conclusions.

The composition 60 Cr + 25 Fe + 15 Mo is erosion resistant under conditions of hyper-velocity. The hot hardness is also great enough to resist swaging under engraving stresses.

The elimination of the tendency to crack and the reduction of the grain size will produce gun liners suitable for a hyper-velocity gun.

3. Tantalum Liners.

The tantalum liners described in this section were prepared by the Fansteel Metallurgical Corporation.

(a) Erosion Resistant Properties of Tantalum. Erosion vent plug tests[1] have shown this metal to be one of the few metals that is resistant to powder gas attack. Since the melting point is somewhat higher than molybdenum it is not surprising that the surface of a tantalum liner should show no signs of thermal erosion by the powder gases.

However, because of the scarcity of the metal it could not be supplied in the quantities required for gun liners.

(b) Erosion Tests on Tantalum Liners.

(1) Variables Tested. The following variables were tested in the firing tests described below:

(a) Smooth bore liner

(b) Rifled liner

(2) Summary of Results. Two liners were tested with double base powder. The details of these tests are given in the Appendix (page 121). The results of these tests show

(a) There was no evidence of powder gas erosion.

(b) Roughening of the tantalum surface indicated there might be some galling action between the tantalum surface and the bullet.

(c) There was no cracking of the surface. This indicated the tantalum has a high resistance to thermal shock.

(d) The tantalum tested was not hard enough to withstand the abrasive action of the bullets. Further work would be necessary to harden the tantalum to make it satisfactory for a gun liner.

(3) Conclusions.

Tantalum resists erosion under hyper-velocity conditions, but its scarcity prevents its use as a material for gun liners.

4. Stellite Liners.

The stellite liners described in this section were bore-drilled and rifled at the Crane Company under Contract OEM-sr 915.

(a) Erosion Resistant Properties of Stellite. Stellite is a "hot-hard" alloy, having a hardness high enough to resist swaging of the lands during engraving. It is essentially a cobalt-chromium-molybdenum or tungsten alloy and is resistant to chemical attack by the powder gases.

However, it has a melting point lower than gun steel, being 1250° - 1300°C.

The property of prime importance is the high resistance to bullet wear (swaging and friction).

(1) Types of Failure Observed. In general, the types of failure observed in the testing of these liners may be attributed to:

Low Melting Point. Melting of the surface in all liners tested with double base powder (flame temperature 3560°K).

The types of failures observed are as follows:

(a) Melting of the bore surface by double base powders.

(b) Surface cracking caused by the thermal stresses at the bore surface.

(b) Erosion Tests on Stellite Liners.

(1) Variables Tested. The following variables were tested

in the firing tests outlined below:

(a) Composition. The stellite #22 liners have approximately 4.5% tungsten and in the stellite #21 liners the tungsten is replaced by molybdenum.

(b) Propellant Powder Composition. Stellite liners were tested under hypervelocity conditions using the following powders having different potentials and flame temperatures:

	IMR	RDX (CR. 1 Type)	Double Base (20% N.G.)
Nitrocellulose	86.70	50.0	77.83
Nitroglycerin	-	-	20.09
Dinitrotoluol	8.74	10.0 (coating)	-
Cyclonite	-	45.0	-
Dibutyl Tartrate	-	4.5	-
Potassium Sulphate	0.65	0.7	1.09
Diphenylamine	0.77	0.5	0.76
Adiabatic Flame Temp. (°K)	2940	2965	3560
Velocity of Projectile at 26 ft. in f.p.s.	3500	3625	3700

(2) Summary of Results. Table X gives a list of the stellite liners tested in this program. The details of each firing test are given in the Appendix (page 122).

The results of the liners tested show:

(a) Stellite is not resistant to thermal attack by double base powders. Melting of the surface occurs during one round and it is practically impossible to establish load.

(b) Stellite is resistant to attack by single base (IMR Type) and RDX (CR. 1 Type) powders at the slow rate of fire in the Caliber .50 Erosion Testing Gun.

A comparison of the extent of failure of the stellite liner with double base powder after 85 rounds, with IMR powder after 1562

TABLE X - SUMMARY OF FIRING TESTS ON STELLITE LINERS

F = Failure   S = Satisfactory

Test	Stellite Liner	Bullet	Powder	Rds. Fired	Swaging	Cracking of Liner Long.	Cracking of Liner Transverse	Surface Cracking	Gas Erosion
E(F22)	#22	B.M2	D.B.	85	-*	S	S	F	F
E(F25)	#22	B.M2	D.B.	25	-*	S	S	F	F
E(F27)	#21	B.M2	D.B.	85	-*	S	S	F	F
E(F28)	#21	B.M2	IMR	509	S	S	S	F	S
E(F34)	#21	B.M2	IMR	1562	S	S	S	F	S
E(F35)	#21	B.M2	RDX - CR1 Type	1028	S	S	S	F	S
Gun Steel Control		B.M2	D.B.	115	-*	S	S	F	F

* Severely eroded by gas erosion (melting).

58-13

rounds and RDX (CR.1) after 1023 rounds is shown on Figure 16 and Figure 17.

Figure 16 gives a comparison of the pressure change as a function of the rounds fired.

Figure 17 gives a comparison of the advance of the land gages and shows a profile of the respective bores after the above number of rounds.

(3) Conclusions.

The success of a stellite liner in any particular gun depends mainly upon the amount of heat (heat input) transmitted to the bore surface.

The amount of heat transmitted to the bore surface is determined by:

(a) The flame temperature of the powder, (b) powder charge, and (c) duration of heating; and in a particular gun the heat input to the bore surface can be changed by -

(i) the rate of fire, (ii) the length of burst, (iii) the cooling interval between bursts, and (iv) the roughness of the bore surface.

Since it has been shown that stellite is resistant to IMR and RDX (CR.1) powders in the erosion testing gun at a rate of fire of 12 R.P.M., this will not be true when the cyclic rate of fire is changed.

The low melting point of stellite is a limiting factor in its use as a liner for a hyper-velocity gun.

FIG. 16 - COMPARISON OF PRESSURE CHANGE IN STELLITE #21 LINERS FIRED WITH VARIOUS POWDERS

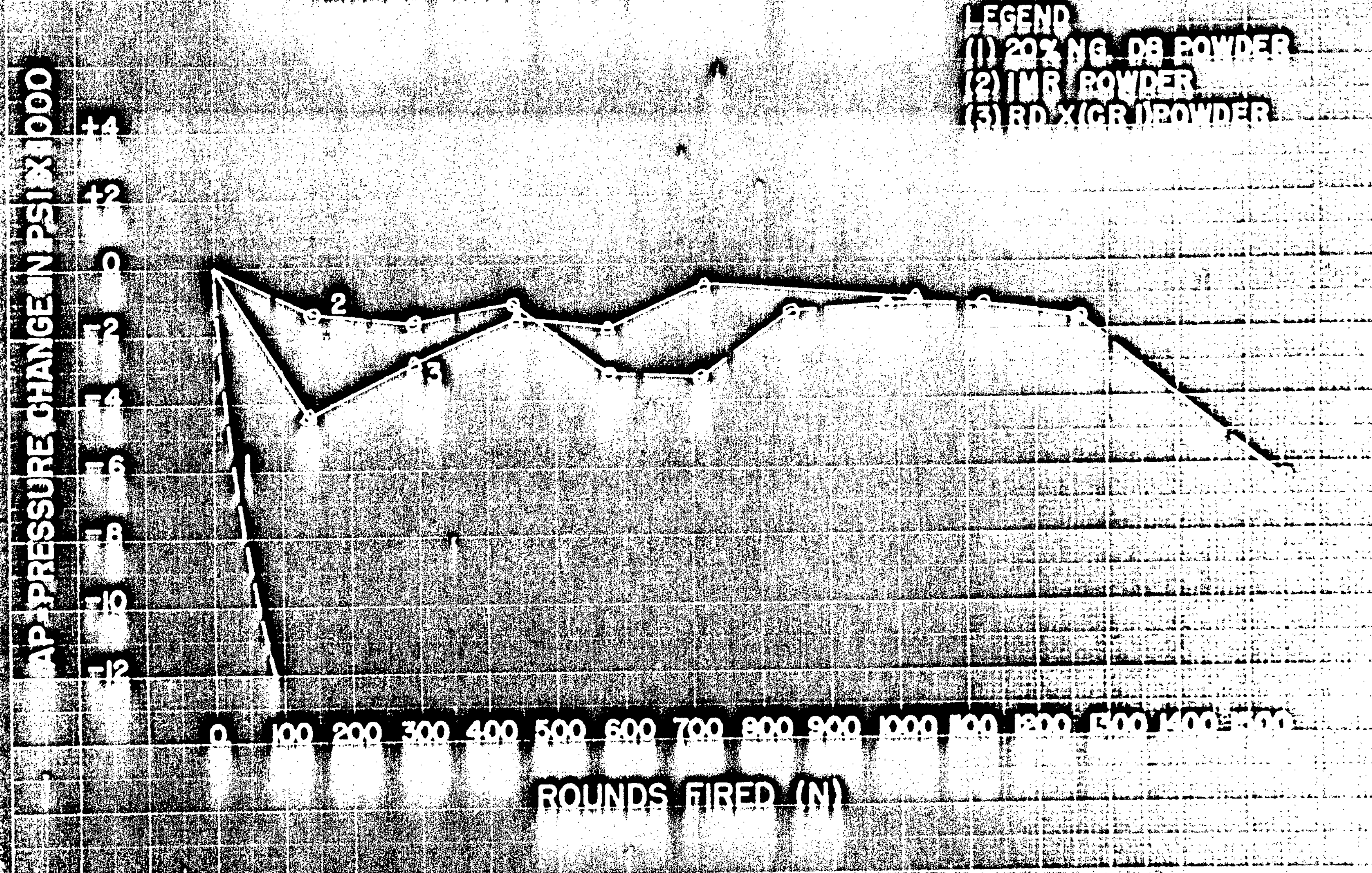
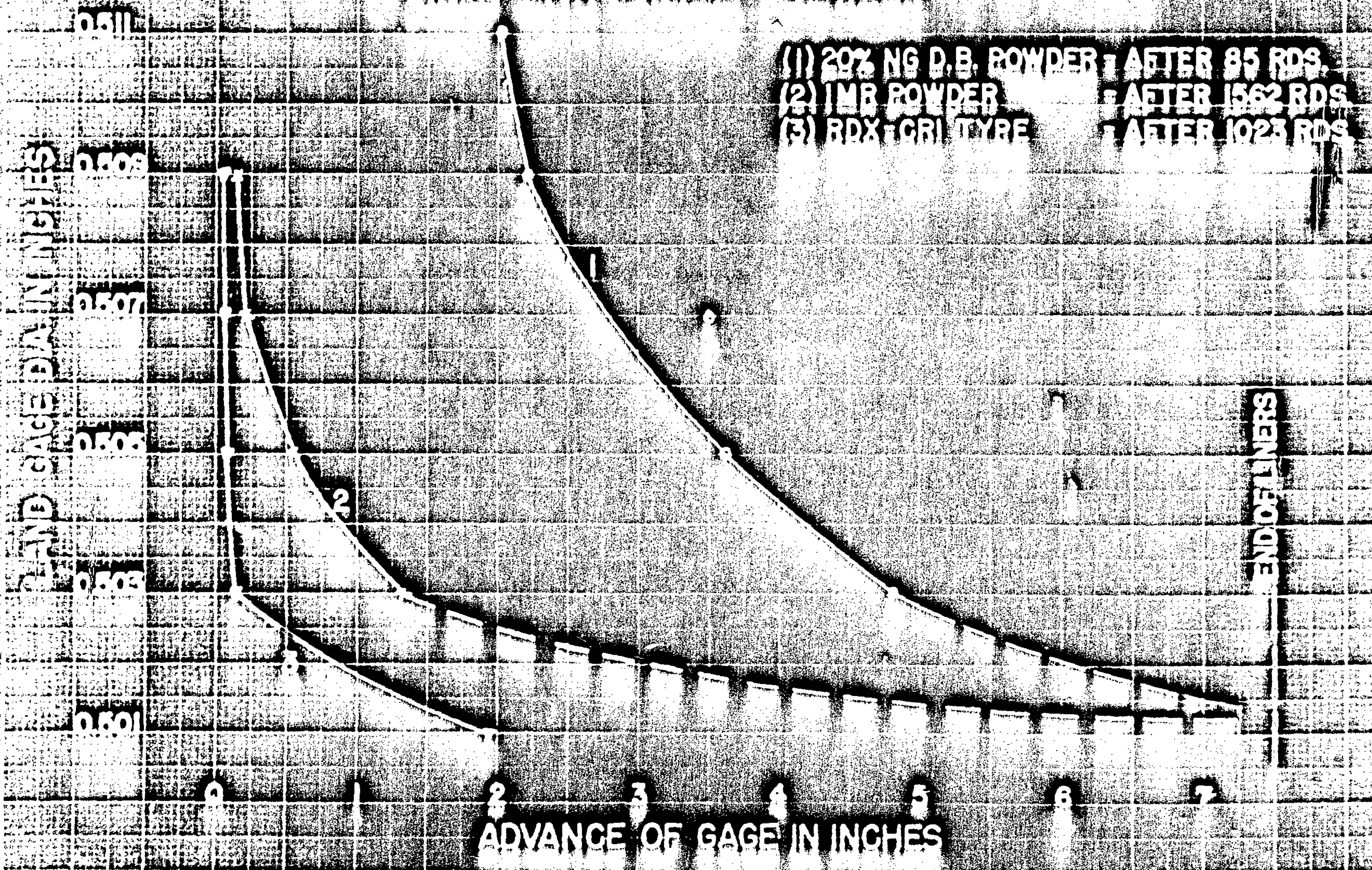


FIG. 17 - COMPARISON OF EROSION OF STELLITE #21 LINERS FIRED WITH VARIOUS POWDERS



5. Nickel Base Alloys.

The tensile strength and hot hardness of some nickel alloys, especially Z-nickel, are satisfactory for gun liners.

Table XI gives a list of the nickel base alloys tested. The details of these tests are given in the Appendix (page 125).

The test data show:

(1) Monel metal gave the same groove erosion as gun steel but the land erosion was twice as great. This indicates greater bullet wear of the monel metal lands.

(2) Z-nickel. The erosion observed was unlike that of gun steel in that the deep thermal cracks were absent, but the surface of the metal on both lands and grooves had a pitted appearance as if chunks of metal had been torn loose from it. Gage measurements showed that the loss of metal differed little from that of gun steel under the same conditions. This type of erosion, namely, where cracking takes place along the crystal boundaries, is characteristic of nickel and its alloys.

(3) Zirconium nickel. The grooves showed little wear but severe thermal cracking around the nickel crystals. The lands were worn more severely than those of gun steel under the same conditions. For two inches beyond the O.R. the lands were flattened out showing insufficient strength to withstand the engraving stresses.

(4) Conclusions. Nickel base alloys fail by intergranular attack and are not suitable as gun liners under conditions of hypervelocity.

TABLE XI - SUMMARY OF FIRING TESTS ON NI BASE ALLOY LINERS

F = Failure S = Satisfactory

Test	Liner	Bullet	Powder	Rds. Fired	Swaging	Cracking of Liner Long.	Cracking of Liner Transverse	Surface Cracking	Gas Erosion
E(F8)	Monel	B.M2	D.B.	55	-*	S	S	F	F
E(F9)	Z-Nickel	B.M2	D.B.	70	-*	S	S	F (pitting)	F
E(F15)	Zirconium Nickel	B.M2	D.B.	45	F	S	S	F	S
Gun Steel Control		B.M2	D.B.	115	-*	S	S	F	F

* Severely eroded by gas erosion (melting).

L3-15

6. Silicon Steel Liner.

X-ray examination, by Dr. Posjnak of the Geophysical Laboratory, of the bore surface of guns fired with double base powder showed a high percentage of oxide of iron. Firing tests with iron powder and ferrosilicon powder mixed with the double base powder by Dr. Posjnak showed that the reducing properties of ferrosilicon powder had prevented the formation of iron oxide. It was hoped that the addition of silicon to steel would also prevent the formation of iron oxide on the bore surface.

A liner of silicon steel, containing approximately 4.7% silicon, was fired 7 rounds. The liner cracked so badly it was impossible to continue the test. The grain size was so large that the material was too brittle for use as a liner material.

D. FILMS AND COATINGS

1. Chromium Plate.

The electroplating of the liners described in this section was done at the National Bureau of Standards, except where otherwise indicated. The conditions and details of the plating procedure may be obtained from the Bureau of Standards Report.

(a) Erosion Resistant Properties of Chromium. Chromium has a melting point that is high enough to resist melting in the bore of a gun and is also chemically resistant to the powder gases. Erosion vent plug tests (1) have shown this metal to be one of the few metals that is resistant to powder gas attack.

However, the metal has very little ductility.

(1) Types of Failure Observed. In general, the types of failure observed in the testing of chrome plated guns may be attributed to:

Low Ductility of Chrome Plate. The checker-work cracking which appears on chrome surface is due to the inherent low ductility and brittleness of chrome plate.

Formation of Altered Steel Layer. See paragraph (f) on page 46.

The types of failure observed are as follows:

(a) Cracking of the chrome plate producing a block pattern.

(b) Pitting of the chrome plate caused by the removal of a crack-isolated block of chromium.

(c) Abrasion of the chrome plate on the driving edge of the lands.

(d) Scoring of the exposed gun steel and undercutting of the chrome plate.

(2) Mechanism of Chrome Plate Failure under Hyper-velocity Conditions. The erosion of chromium plated bores, presents two separate problems: (1) the erosion of the barrel, which controls primarily the accuracy life of the gun; and (2) the erosion of the forcing cone, which controls primarily the muzzle velocity of the bullet. The failure of the chrome plate, if it has been plated properly, always begins at the breech end of the plated bore with the result that the accuracy life is always greater than the velocity life of the gun.

Observations show that the failure of the chrome plate usually follows the same pattern. Briefly, this pattern is as follows:

(a) Pronounced cracking of the Chrome Plate. There is some evidence that cracks in the chrome plate are formed during electrodeposition. Such cracks often originate at the non-metallic inclusions in the chromium-steel interface and occasionally do not reach the top surface of the chromium.

After firing a few rounds, these cracks are wider and if not originally present, a new set of cracks has formed due to the expansion of the bore by the firing pressure. Also the chrome plate has been heated by the powder gases and in partially annealing contracts linearly, varying from 0.1% for L.C. chrome plate to 1.0% for H.C. chrome plate.

The stresses on the chrome plate surface set up by the above conditions are too high for the brittle chrome plate with the

66-13

result that the plate cracks. The production of a more ductile plate would greatly help the performance of the chrome plate.

(b) Curling up of the Edges of the Blocks, thereby Giving the Surface a Wrinkled Appearance. The stresses and changes occurring at the bore surface during firing soon cause the edges of the chrome plate blocks to curl up. This usually results in increased resistance to the movement of the projectile resulting in an increase in powder pressure.

(c) Pitting or Removal of Small Blocks of Chrome Plate in the Bore Area beyond the Forcing Cone. This behavior is an advanced result of the failures described under (a) and (b) above. The impact and the friction of the bullet cause movement of the blocks of plate. Metallographic examination (2) has shown blocks which are no longer aligned with one another.

Continued impact on these blocks soon cause their removal leaving exposed steel in the case of the thicker plates or exposed altered layer in the case of the thinner plates.

(d) Removal of Chrome Plate from the Edge of the Bullet Seat. Because of the geometry of the bullet seat, the edge is probably the hottest part of the bore. Failure of the plate usually starts at this point and continued firing causes undercutting of the remaining chrome plate on the bullet seat area and the advance of the plate failure.

(e) Removal of Chrome Plate from the Lands. Engraving types of bullets cause complete plate removal from the land area. This usually starts at the point where the lands reach their greatest height.

(2) Harvard Report, "Metallographic Examination of Gun Liners and Coatings Tested Under Hypervelocity Conditions".

67-13

This failure suggests that the steel beneath the chrome plate is deformed slightly.

With pre-engraved bullets the removal of chrome plate starts at the driving edge of the lands. Continued firing causes the advance of the plate failure toward the muzzle and across the lands to the non-driving edge until the plate is completely removed from the land area. The rate of failure, however, is considerably less than the rate of failure occurring with the engraving type of bullets.

(f) Spalling or Removal of Large Areas of Plate due to Undercutting of the Plate. The increase in the width of the cracks permits the hot gases to reach the steel beneath the plate. In thin plates, the cracks traversing the chromium mushroom into cavities where they meet the altered steel. These cavities confine themselves to the altered layers and seldom penetrate into unaltered steel. Growth of these cavities soon undercuts the chrome plate and causes the removal of large areas of plate.

However, if the chrome plate is thicker than the critical thickness necessary to prevent the formation of the altered steel layer, there is no undercutting and the chromium adheres well to the steel surface.

The pitting of the chrome plate surface described under (c) produces small areas of exposed steel or areas of thinner plate which are now local points of weakness in the plated surface. Continued firing soon causes undercutting of the adhering plate emanating from these areas of weakness.

(b) Erosion Tests on Chrome Plated Bores.

(1) Variables Tested. The following variables were tested in the firing tests listed in Table

(a) Types of Chrome Plate. Two types of chrome plate were tested: namely, Standard chrome plate, designated as H.C. (High Contraction) because of its high linear contraction when heated, and Low Contraction chrome plate, designated as L.C.

(b) Types of Bore Surface. Chromium was plated on 2 types of surfaces: namely, machined gun steel, and electropolished gun steel.

(c) Thickness of Plate. Plate thickness varied from 0.7 mil to 10 mils.

(d) Types of Projectile. Three types of bullets were fired: engraving type, such as Ball M-2 and copper banded artillery type, pre-engraved steel banded, and lubricated pre-engraved steel banded (Parco-Lubrized).

(e) Types of Powder. Three types of powder were used; IMR, 20% N.G. Double Base, and Ballistite, a double base powder containing 40% nitroglycerin.

(2) Summary of Results.

Table XII gives a list of the chrome plated liners and barrels tested in this program. The details of each firing test are given in the Appendix (page 127.

A summary of the results of the variables tested is as follows:

(a) Type of Chrome Plate. Two types of chrome plate

69-13

CONFIDENTIAL

TABLE XII - SUMMARY OF FIRING TESTS ON CHROME PLATED LINERS AND BARRELS

Test	Plate	Thickness	Bullet	Powder	Rds. Fired	Advance of Land Care 0.505"	Advance of Land Care 0.493"	Pressure Drop psi.	Velocity Drop fps.	Rounds for ΔV = -200 fps.
J(F3)	Standard	.0007"	B.M2	D.B.	45	+0.24	-	-3200	-168	-
J(F7)	"	.001	"	D.B.	115	+1.36	-	-3600	-	-
J(F9)	"	.001	"	D.B.	115	+1.60	-	-5300	-217	110
J(F10)	"	.001	"	D.B.	115	+0.70	-	-11000	-220	105
J(F11)	L.C.	.001	"	D.B.	115	+0.50	-	-4500	-107	-
J(F15)	Standard	.001	A.T.	D.B.	150	+1.4	+1.8	-9200	-246	70
J(F6)	"	.001	P.E.	D.B.	115	0.0	-	+8200	+ 73	-
J(F12)	"	.001	"	D.B.	150	+0.13	+0.23	-1900	- 56	-
J(F13)	L.C.	.001	"	D.B.	150	+0.10	+0.13	+2200	- 41	-
J(F100)	Standard	.00235	P.E.	IMR	820	+2.87	+8.17	-8400	-245	710
J(F73)	"	.003	"	40% N.G. D.B.	98	+1.10	+1.54	-3100	-163	120
J(F79)	"	.0055	"	FNH M2	510	+1.34	+2.04	-6500	-237	470
J(F102)	Standard	.004	P.E.	40% N.G. D.B.	147	+1.06	-	-7000	-229	130
J(F113)	"	.004	"	IMR	1232	+1.45	+2.2	-3400	-212	1165
J(F60)	"	.0045	"	FNH M2	570	+0.42	+2.31	-9200	-305	490
J(F14)	Standard	.005	B.M2	D.B.	115	+0.10	-	+1800	- 66	-
J(F24)	"	.005	A.T.	D.B.	228	+0.2	+0.27	-5800	-121	-
J(F27)	"	.005	"	D.B.	381	+0.8	+0.85	-13200	*	-
J(F20)	L.C.	.005	"	D.B.	220	+0.2	+1.7	-9200	-294	170
J(F34)	"	.005	"	D.B.	291	+0.1	+0.2	-9300	-350	165
J(F40)	"	.005	"	D.B.	311	+0.51	+1.6	-14400	-333	225
J(F8)	Standard	.005	P.E.	D.B.	115	0	-	-2800	-133	-
J(F17)	"	.005	"	D.B.	430	0	0	+3500	+ 8	-
J(F18)	"	.005	"	D.B.	430	0	0	-1500	- 62	-
J(F112)	"	.005	"	FNH M2	825	+0.3	+0.3	-3100	-258	765

CONFIDENTIAL

70-15

TABLE XII (Continued)

Test	Plate	Thickness	Bullet	Powder	Rds. Fired	Advance of Land Case 0.505"	Advance of Land Case 0.493"	Pressure Drop psi.	Velocity Drop fps.	Rounds for ΔV = -200 fps.
L1(F18)	Standard	.005"	P.E.	D.B.	2775	+1.2	>25	-13800	-555	1875
J(F18)	L.C.	.005	"	D.B.	440	0	0	+ 300	- 57	-
L1(F8)	"	.005	"	D.B.	1007	+1.9	+21.0	-4500	-220	975
J(F104)	Standard	.008	P.E.	IMR	3112	+0.2	+0.3	-6000	-231	2970
J(F111)	"	.00825	"	40% N.C. D.B.	282	+2.4	+2.79	-16900	-642	180
J(F41)	Standard	.010	A.T.	D.B.	88	0	0	+8300	*	-
C(F6-F12)	Gun Steel Control		A.T.	D.B.	150	+5.79	>25	-14550	-332	95
L1(F5-F9)	Gun Steel Control		P.E.	D.B.	290	+7.28	>25	[illegible]	-287	241
J(F108)	Gun Steel Control		P.E.	FNH M2	146	+4.25	>25	-5680	-207	148
L1(F19)	Gun Steel Control		P.E.	IMR	441	+3.08	>25	-6058	-277	382

* Keyholing bullets.

71-13

were tested: (1) Standard, or High Contraction (H.C.), and (2) Low Contraction.

The essential differences in these two types of plates are:

(1) Standard plate contracts linearly, about 1.0% and low contraction plate contracts about 0.1% when heated to 1200°C.

(2) Standard plate has a hardness of about 900 Brinell and L.C. plate has a hardness of about 500 Brinell.

(3) L.C. plate has a lower chromium oxide content.

The plating conditions are also different. Standard plate is usually deposited at 50°C and 20 amperes per square decimeter. Low Contraction plate is deposited at 85°C and 80 amperes per square decimeter. The exact conditions and procedure for plating may be obtained from the Bureau of Standards Report.

A comparison between the performance of the H.C. and L.C. plates was made with 1 mil and 5 mil plate thickness using both engraving types of bullets and pre-engraved bullets.

The summary of the 1 mil results was obtained from Tests J(F10), J(F11), and J(F15) for the engraving type bullets and from Tests J(F6), J(F12), and J(F13) for the pre-engraved type bullet. The results of these tests show:

(1) Using engraving type bullets (Ball M-2 and A.T.), the L.C. plate was slightly better at the beginning, but as firing continued, plate failure on the lands and grooves was greater than observed with H.C. plate.

(2) Using pre-engraved bullets, the L.C. plate is less cracked, more adherent and generally less eroded than H.C. plate.

The summary of the 5 mil results was obtained from Tests J(F20), J(F24), J(F27), J(F34), and J(F40) for the engraving type bullets and from Tests J(F16), J(F17), J(F18), and L1(F8) for the pre-engraved type bullet.

The results of these tests show:

(1) Using engraving type bullets the type of plate applied to the bore surface is of little importance.

(2) Using pre-engraved bullets there is less pitting of the L.C. plate and less wear on the driving edge of the L.C. plated lands. In general L.C. plate was slightly better than H.C. plate when pre-engraved bullets were fired.

However, because of the difficulties encountered in plating 45 inch barrels with L.C. plate to the desired dimensions, the slight improvement in performance did not warrant further development.

(b) Type of Bore Surface Plated. Chrome plate was deposited on two types of gun steel surface: namely, electropolished and machined.

Machining may leave burrs and rough edges on the land corners, which are points for rapid "treeing" of the chrome plate during the plating operation. These high points are soon knocked off in the first firing thereby either exposing small areas of gun steel or producing areas of thinner chrome plate which are more susceptible to thermal failure.

Comparison of Tests J(F14), J(F27), J(F34), and J(F40) which were electropolished, with Tests J(F24), J(F20), J(F17), and J(F18) which were machined oversize for the chrome plate, shows that superior performance is obtained from chrome plate deposited on an electropolished surface.

As a result of these tests it has been the procedure in all firing tests of chrome plated barrels to electropolish oversize for the thickness of the chrome plate to be deposited. However, it is not necessary to remove the entire amount by electropolishing. It has been our procedure for thick chrome plates to machine oversize all but the last .002" on the radius and then electropolish the remaining .002".

(c) Thickness of Chrome Plate. Altered layers, similar to those formed on unprotected steel, are observed in the steel underlying thin chrome plates. When the steel is protected by plating, the hot gases should have little access to the steel except at cracks in the plating. Nevertheless, altered steel was not observed concentrated about these cracks. These facts suggest that when the bore surface is coated with a protective material, heating and cooling cycles are the most important cause of alteration of the steel.

Since the formation of the altered layer is a thermal affect, the thickness of the altered layer produced is a function of the plate thickness and heat content of the powder gases. To prevent the formation of the altered layer, the chrome plate should be thick enough so that the temperature at the steel-chrome plate interface is below the transition temperature of the gun steel.

Because of the transformation of the gun steel at the interface, thin plates add very little to the performance of the gun.

To determine the effect of plate thickness on velocity life, several barrels were fired with different types of powder using pre-engraved bullets. The plate thickness varied from .002" to .006" and were deposited on electropolished surfaces.

The powders used were single base IMR type, a double base powder containing 20% nitroglycerin, and a double base powder containing 40% nitroglycerin, having flame temperatures of 2940°K, 3560°K, and 3945°K, respectively. The results of these tests are shown graphically on Figure 18.

These data show:

(1) .006" chrome plate gives little improvement over gun steel when a 40% N.G. powder is used.

(2) The best performance is obtained with a plate that is .006" thick when 20% N.G. and IMR powders are used.

Borescope examination of the plated surface at different stages showed that less cracking is observed with the thinner plates and very pronounced cracking is observed with the thicker plates. In a series of firings to determine the thickness of plate required to prevent the formation of the altered layer (Tests J-F61 to J-F72), examination showed fracture and removal of the plate from the lands when the plate thickness was .008". This removal was due entirely to the brittle nature of the chrome plate.

Until the ductility of the chrome plate is improved, it appears that the optimum chrome plate thickness is .006" to .007" for a hyper-velocity gun.

Ballistic performance and metallographic examination are in good agreement. The best performance is obtained with .005" to .006" chrome plates and if the plate is that thick, no altered layer is formed at the interface. The shorter velocity life with the thinner plates is confirmed by metallographic examination. Altered layers are formed beneath the thin plates and undercutting of the plate by erosion of the altered layer soon occurs after a short number of rounds.

FIG 18 - EFFECT OF CR. PLATE THICKNESS ON VELOCITY LIFE
PRE-ENGRAVED BULLETS AND VARIOUS POWDERS

(d) Types of Projectile. The lack of ductility in the chrome plate is very clearly shown in the comparison between the performance with pre-engraved bullets and the usual engraving type bullets. The engraving stresses and abrasive wear on the chrome plate surface produced by the engraving of the projectile very materially shorten the life of the chrome plate.

Three types of bullets were tested: namely,(1) engraving types such as Ball M-2 and copper banded artillery bullets, (2) steel pre-engraved bullets, and (3) lubricated (Parco Lubrized) steel pre-engraved bullets.

The steel pre-engraved bullet reduces the engraving stresses to a minimum, and the lubricated pre-engraved bullet reduces the abrasion due to friction to a minimum. The type of bullet used does not affect the frequency and the depth of cracking of the chrome plate, nor the thickness of the altered layer formed at the steel interface.

A comparison of the behavior of .005" chrome plate using artillery type, steel pre-engraved and Parco Lubrized pre-engraved bullets is shown graphically in Figure 19.

The chrome plate protects the steel surface for a definite period. This period of protection is much shorter for the engraving type bullets. As soon as gun steel is exposed to the erosive effects of the powder gases, the rate of erosion increases very rapidly. Parco Lubrized pre-engraved bullets give the longest protection period and the lowest erosion rate after the gun steel has been exposed.

The effect of the bullet type on performance of the .005" chrome plate is shown in the following table:

FIG. 19 - PROGRESS OF LAND EROSION
COMPARISON OF RATE OF BORE ENLARGEMENT AT 1/2" BEYOND OR
DOUBLE BASE POWDER & VARIOUS TYPE BULLETS

TABLE XIII

Effect of Bullet Type on Chrome Plate Performance

Test	Bore Surface	Powder	Bullet	Rounds Fired for a Velocity Drop of 200 f.p.s.
C(F6, 12)	Gun Steel	D.B.	A.T.	95
L1(F5, 9)	Gun Steel	"	P.E.	240
J(F20, 34, 40)	.005" Cr	"	A.T.	220
L1(F8)	.005" Cr	"	P.E.	975
L1(F18)	.005" Cr	"	Parco-Lubrized P.E.	1875

The progress of velocity change is shown graphically on Figure 20.

These results show: (1) the performance of the chrome plate is greatly influenced by the type of bullet that is used; (2) engraving stresses and friction play an important part in the failure of the chrome plate; (3) and the best performance is obtained with a lubricated (Parco-Lubrized) pre-engraved bullet.

(e) Types of Powder. One of the main factors in the failure of chrome plate is the formation of an altered steel layer at the interface. Since the formation of this altered layer is a thermal transformation, it is not surprising that the flame temperature of the powder used is an important factor in the ballistic performance of the chrome plated gun.

Several barrels were plated with .005" to .006" chrome plate on electropolished gun steel and fired with pre-engraved bullets.

Three types of powder were used: namely, single base IMR type, a double base powder containing 20% nitroglycerin, and a double base powder containing 40% nitroglycerin.

19-13

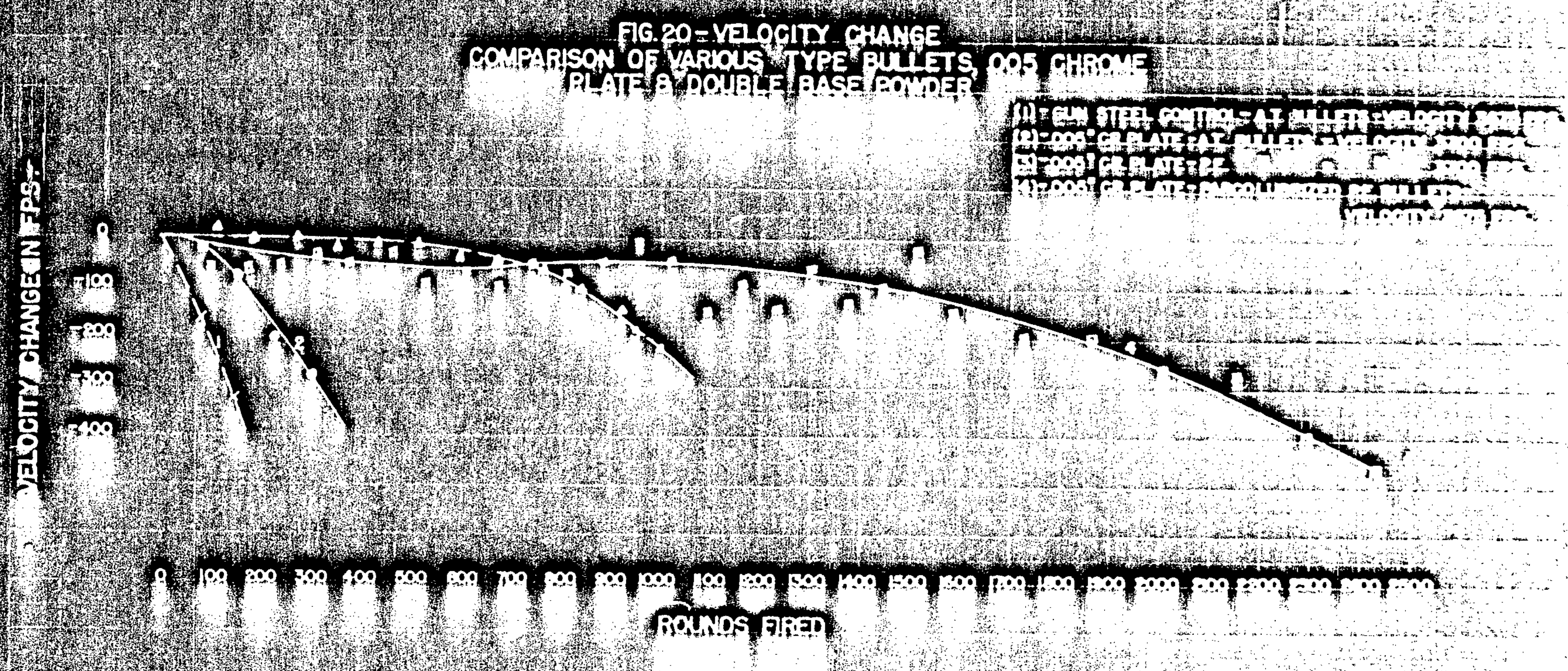


FIG. 20 - VELOCITY CHANGE
COMPARISON OF VARIOUS TYPE BULLETS, .005 CHROME PLATE & DOUBLE BASE POWDER
VELOCITY CHANGE IN FPS
0
100
200
300
400
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500
ROUNDS FIRED

The flame temperatures of these powders were 2940°K, 3560°K and 3945°K, respectively. The barrels were fired until a drop in velocity of 200 f.p.s. was observed.

A comparison of the land erosion at the origin of rifling is shown graphically on Figure 21 for:

1. Plain gun steel and .006" Cr plate using 40% nitroglycerin powder.

2. Plain gun steel and .005" Cr plate using 20% nitroglycerin powder.

3. Plain gun steel and .006" Cr plate using IMR powder.

The effect of the powder flame temperature on the performance of the chrome plate is shown in the following table:

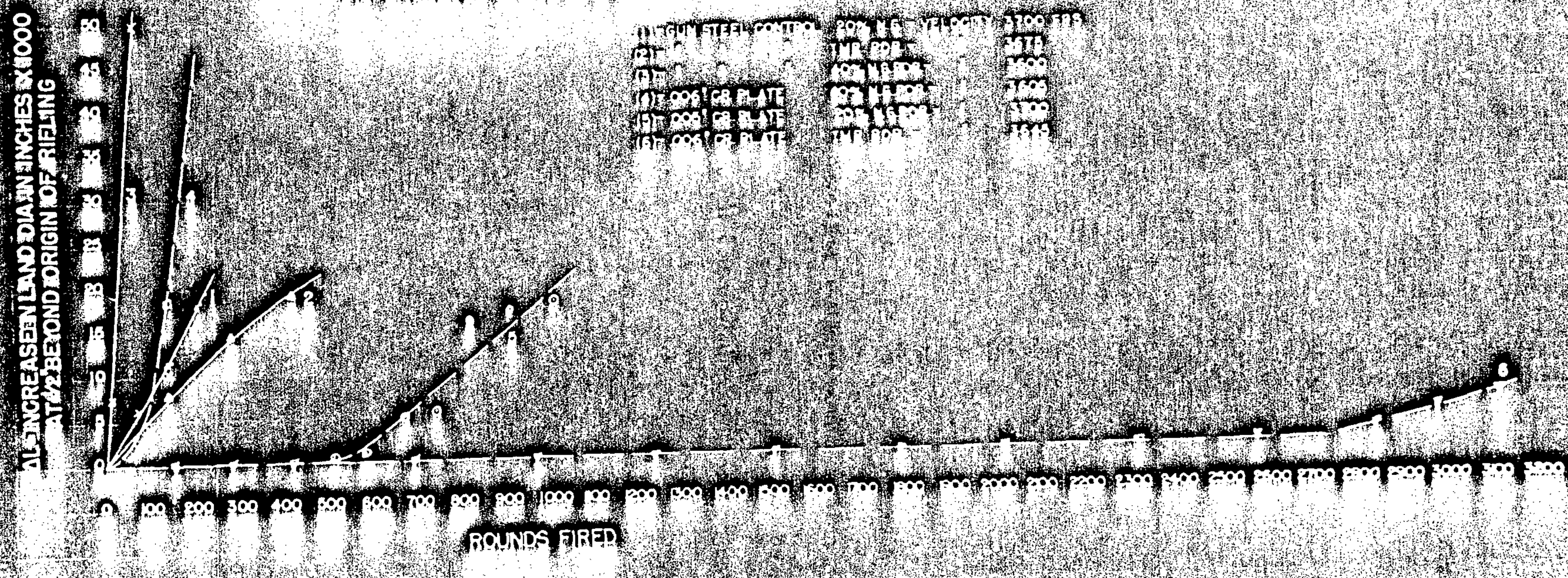
TABLE XIV
Effect of Powder Type on Chrome Plate Performance

Test	Bore Surface	Powder	Flame Temperature	Bullet	Rounds Fired for a Velocity Drop of 200 f.p.s.
K(F43)	Gun Steel	40% N.G.	3945°K	P.E.	70
J(F111)	.006" Cr	40% N.G.	3945°K	"	100
L1(F5, 9)	Gun Steel	20% N.G.	3560°K	"	240
L1(F8)	.005" Cr	20% N.G.	3560°K	"	975
L1(F19)	Gun Steel	IMR	2940°K	"	355
J(F104)	.006" Cr	IMR	2940°K	"	2970

The progress of velocity change is shown graphically on Figure 22.

These results show: (1) .006" chrome fails to protect gun steel against the erosive effects of a 40% N.G. powder. The failure of the Cr plate started at the edge of the bullet seat and advanced very rapidly. There is a possibility that the Cr plate on the

FIG. 21 - PROGRESS OF LAND EROSION
COMPARISON OF RATE OF BORE ENLARGEMENT AT 1/2" BEYOND O.R.
RM-ENGRAVED BULLETS & VARIOUS POWDERS



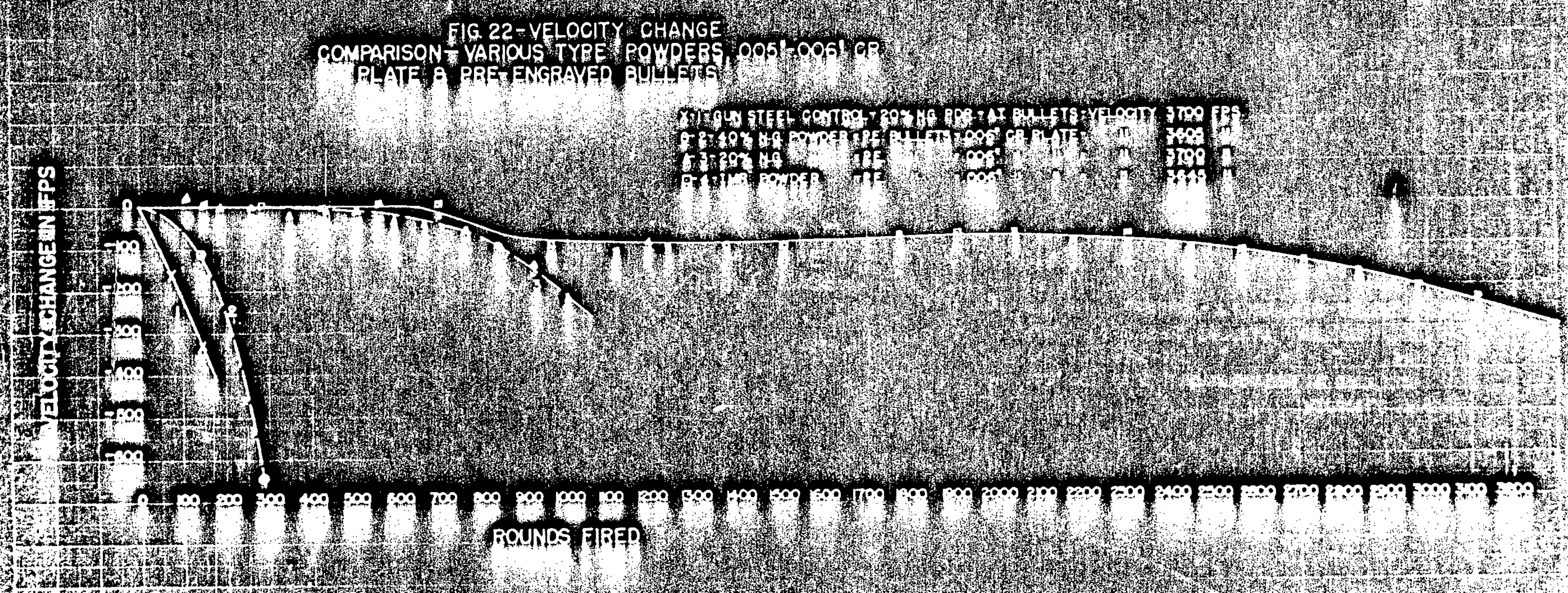


FIG. 22 - VELOCITY CHANGE
COMPARISON - VARIOUS TYPE POWDERS, .005"-.006" CR
PLATE & PRE-ENGRAVED BULLETS
X-1: GUN STEEL CONTROL - 20% NG PDR - AT BULLETS: VELOCITY 3700 FPS
O-2: 40% NG POWDER - PE BULLETS - .005" CR PLATE " 3605 "
Δ-3: 20% NG " PE " .006" " " " 3700 "
□-4: IMR POWDER " PE " .006" " " " 3645 "
VELOCITY CHANGE IN FPS
0
100
200
300
400
500
600
ROUNDS FIRED
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000 3100 3200

53-13

edge of the bullet seat may have been melted; (2) The best increase in performance of the chrome plate is obtained with the cooler IMR powder. Cr plate increased the velocity life of the gun using pre-engraved bullets and 40% N.G. powder from 70 to 180 rounds, a factor of 2; using 20% N.G. powder from 240 to 975 rounds, a factor of 4; and using IMR powder from 350 to 2970 rounds, a factor of 8.5.

(3) Conclusions.

The data observed in the testing of chrome plated bores show:

(a) Chrome plate is resistant to attack by the powder gases (melting).

(b) Thickness of chromium rather than the type of plate controls the erosion.

(c) An optimum thickness of .006" chrome plate is necessary to prevent formation of an altered steel layer at the interface under the conditions prevailing in the Erosion Testing Gun.

(d) An electropolished surface is better than a machined surface as a base for the chrome plate. It is recommended that for thick chrome plates, the last .002" on radius be electropolished.

(e) The failure of chrome plate is due mainly to the brittleness and lack of ductility of the chrome plate. The mechanical stresses set up during the engraving of the projectile and the thermal stresses produced during the heating of the surface accelerate the failure of the chrome plate.

(f) The optimum thickness of chrome plate (.005" to .006") on a gun steel bore will double the velocity life of a gun when using engraving type bullets (Ball M-2 and A.T.). The improvement of a chrome plated bore using A.T. bullets over gun steel is shown graphically on Figures 23 and 24.

(g) The type of bullet used very materially affects the chrome plate performance. The elimination of engraving stresses by the use of pre-engraved bullets will increase the velocity life of the gun about ten-fold. The further elimination of friction by the use of Parco-Lubrized pre-engraved bullets will increase the velocity life of the gun about twenty-fold.

The improvement of a chrome plated bore over gun steel using pre-engraved and Parco-Lubrized pre-engraved bullets is shown graphically on Figures 25 and 26.

FIG.23-PROGRESS OF LAND EROSION
COMPARISON OF RATE OF BORE ENLARGEMENT AT 1/2" BEYOND OR
ARTILLERY TYPE BULLETS & DOUBLE BASE POWDER

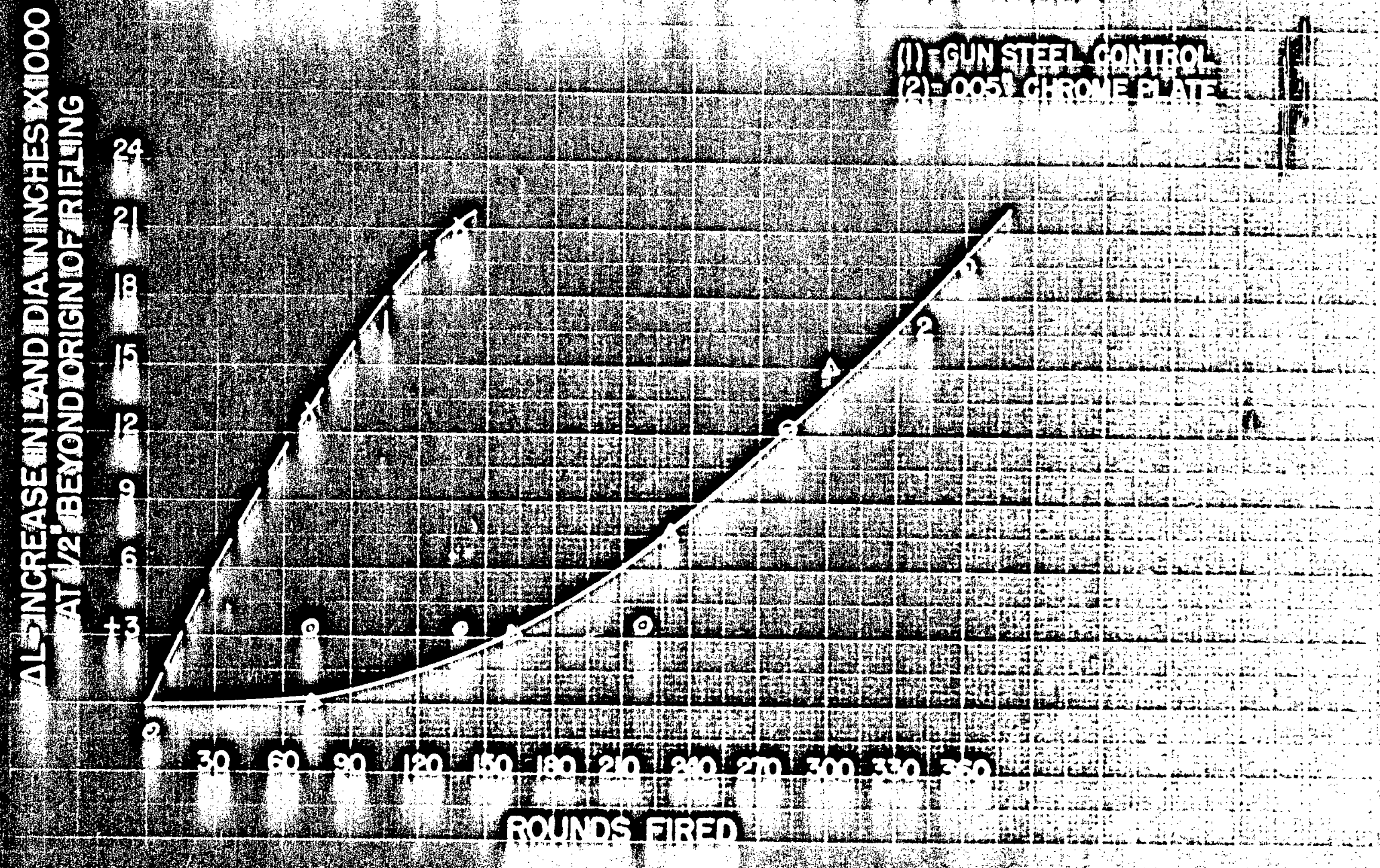
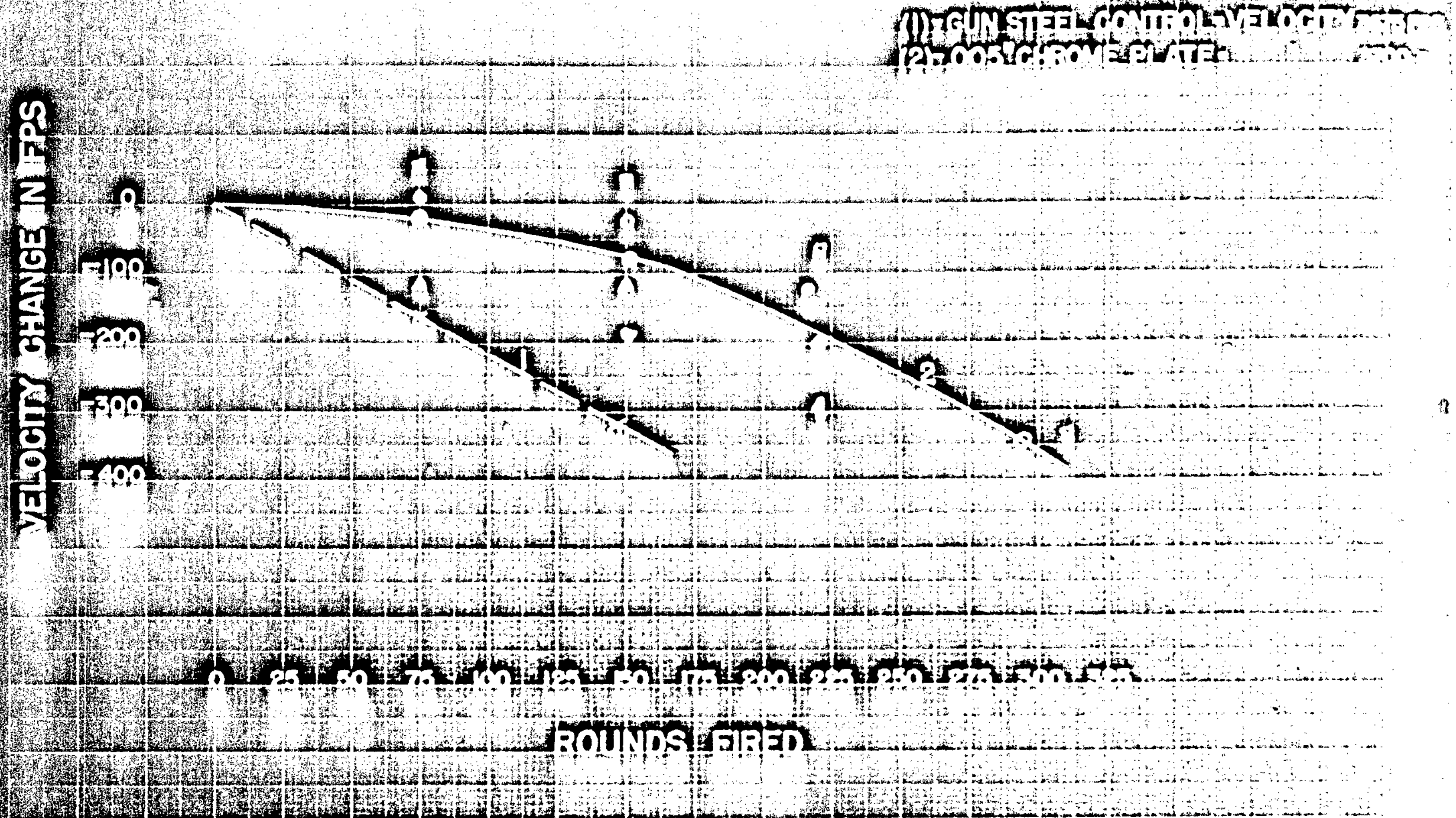


FIG. 24 - VELOCITY CHANGE
COMPARISON .005 CHROME PLATE AND GUN STEEL USING
ARTILLERY TYPE BULLETS & DOUBLE BASE POWDER



2. Cobalt and Cobalt-Tungsten Alloy Plates.

The electroplating of the liners described in this section was done at the National Bureau of Standards. The conditions and details of the plating procedure may be obtained from the Bureau of Standard Reports.

(a) Erosion Resistant Properties of Cobalt and Cobalt-Tungsten Alloys.

The melting point (1420°C) and thermal conductivity of cobalt (0.165 cal/cm^2/sec^2/°C) are approximately the same as gun steel. It is, therefore, not surprising that the cobalt surface should fail by thermal attack (melting).

Cobalt has greater ductility than chromium; however, its lower hardness and greater ductility are such that it may not be able to resist the swaging action of the bullet.

Chemically a cobalt surface is superior to a steel surface.

The addition of tungsten to form a cobalt-tungsten alloy should raise the melting point. At the same time the thermal conductivity is reduced considerably, with the result that the Co-W alloy surface is at a higher temperature than the pure Co surface.

The cobalt-tungsten alloys are harder than cobalt. This hardness can be increased by heat-treatment for one hour at 600°C in Vacuo.

(1) Types of Failures Observed

In general the types of failure observed in the testing of the cobalt and cobalt-tungsten plated liners may be attributed to:

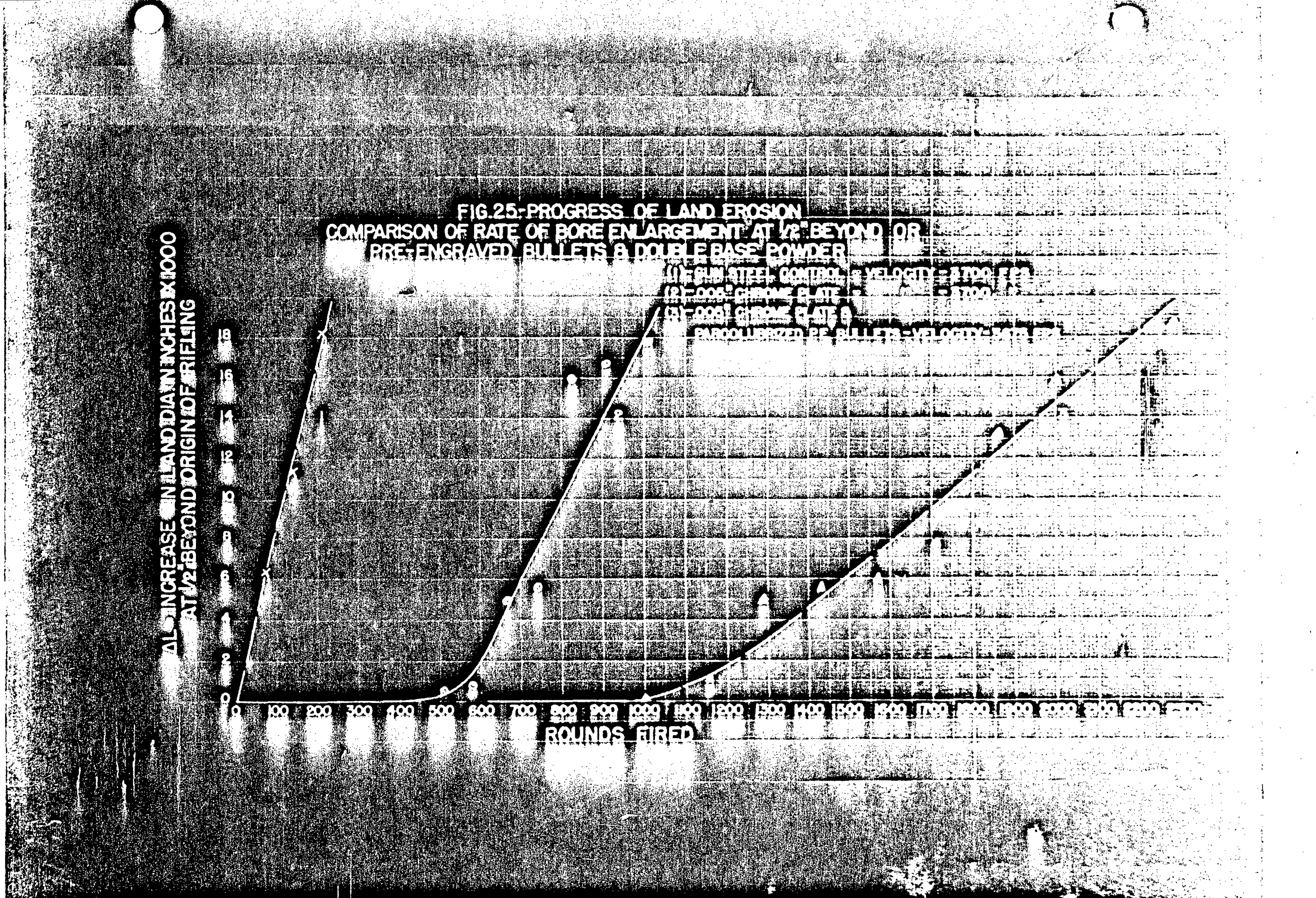
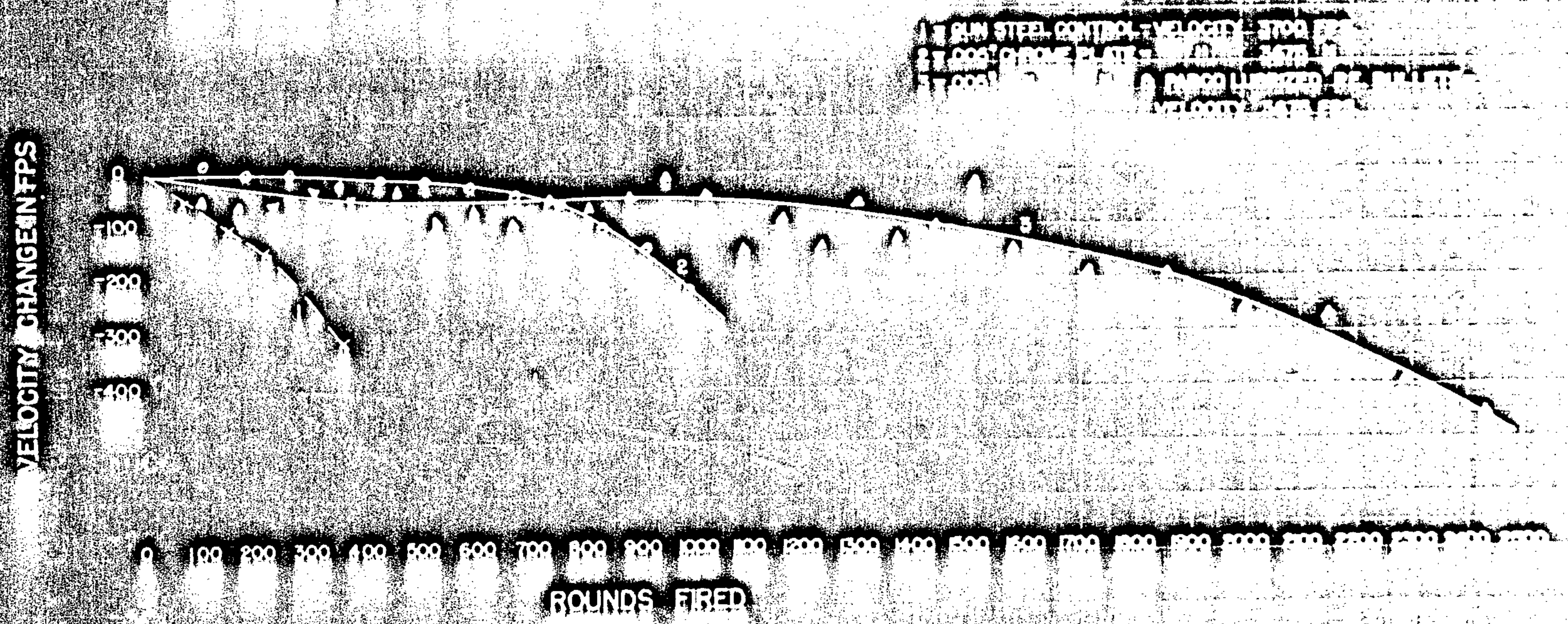


FIG.25-PROGRESS OF LAND EROSION
COMPARISON OF RATE OF BORE ENLARGEMENT AT 1/2" BEYOND OR
PRE-ENGRAVED BULLETS & DOUBLE BASE POWDER
(1)-GUN STEEL CONTROL - VELOCITY - 2700 F.P.S.
(2)-.006" CHROME PLATE
(3)-.006" CHROME PLATE &
ΔL - INCREASE IN LAND DIA IN INCHES X 1000
AT 1/2" BEYOND ORIGIN OF RIFLING
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
ROUNDS FIRED

FIG. 26 - COMPARISON OF VELOCITY CHANGE
.005" CHROME PLATE & GUN STEEL - PRE ENGRAVED BULLETS & D.B. POWDER



Low Melting Point - All the liners tested failed due to gas erosion (melting of the surface). Double Base (20% N.G.) powder was used under standard conditions in all tests.

Poor Adhesion and Brittleness - In the alloy plating containing 20% tungsten the bond to the steel surface was very poor (Test J(F35)).

The types of failure observed are as follows:

(a) Melting and scoring of the plated surface.

(b) Cracking of the Co-W plate.

(b) Erosion Tests on Cobalt and Cobalt-Tungsten Plated Liners

(1) Variables Tested. The following variables were tested in the firing tests outlined below:

(a) Composition of the Plate

Pure Co plate and cobalt plates containing approximately 5%, 14%, 18% and 20% tungsten were tested.

(b) Heat Treatment of the Plate

Some of the cobalt-tungsten plates (Tests J-F35, and J-F38) were given a heat treatment at 600°C in Vacuo for one hour in order to improve the hardness and resistance to the swaging action of the bullet.

(2) Summary of Results

Table XV gives a list of the cobalt and cobalt-tungsten alloy plates tested in this program. The details of each firing test are given in the Appendix (page145). A comparison of the advance of the land plug gages for the cobalt and cobalt-tungsten plated liners and

91-13

CONFIDENTIAL

TABLE XV - SUMMARY OF FIRING TESTS ON COBALT AND COBALT

ALLOY PLATED LINERS

F = Failure   S = Satisfactory

Test	Plate	Thickness	Bullet	Powder	Rds. Fired	Extent of Failure	Advance of 0.505" Land Cage	Gas Erosion
J(F35)	80% Co + 20% W(1)	0.006"	B.M2	D.B.	70	90% off Lands and Grooves	6.8"	F
J(F36)	Co	0.0055"	B.M2	D.B.	155	Lands and Grooves eroded beyond 1" beyond O.R.	0.5"	F
J(F37)	86% Co + 14% W	0.006"	B.M2	D.B.	156	Lands and Grooves eroded full length of liner.	4.5"	F
J(F38)	86% Co + 14% W(2)	0.006"	B.M2	D.B.	70	Areas off full length of liner.	3.9"	F
J(F39)	82% Co + 18% W	0.006"	B.M2	D.B.	150	Adhering - gas eroded full length of liner.	4.6"	F
J(F42)	95% Co + 5% W(3)	0.010"	B.M2	D.B.	86	Adhering - gas eroded full length of liner.	2.0"	F
Gun Steel Control		-	B.M2	D.B.	115	---	8.6"	F

(1) Plating heated at 600°C for 1 hour.
(2) Plating heated at 600°C for 1 hour.
(3) Plated in 2 layers.

CONFIDENTIAL

92-13

and the control gun steel liner is shown on Fig. 27. A summary of the results of the variables tested is as follows:

(a) Composition

One cobalt plated liner was tested (Test J-F36). Severe gas erosion and scoring of the cobalt surface occurred beyond one inch from the origin of rifling. The adhesion of the cobalt plate was excellent and there was no cracking or pitting of the cobalt plate which is characterisitic of chromium plate. Slight swaging of the lands was also observed.

However, the plate lacked the thermal characteristics to resist melting by the powder gases under hypervelocity conditions.

Four cobalt-tungsten alloy plated liners in which the tungsten content varied from 5% to 20%, were tested (Tests J-F35, J-F37, J-F39 and J-F42).

The results of these tests show: (1) poor resistance of cobalt-tungsten plates to gas erosion (melting), (2) increased brittleness and cracking with increasing tungsten content, (3) poor adhesion of the 20% tungsten plate to gun steel.

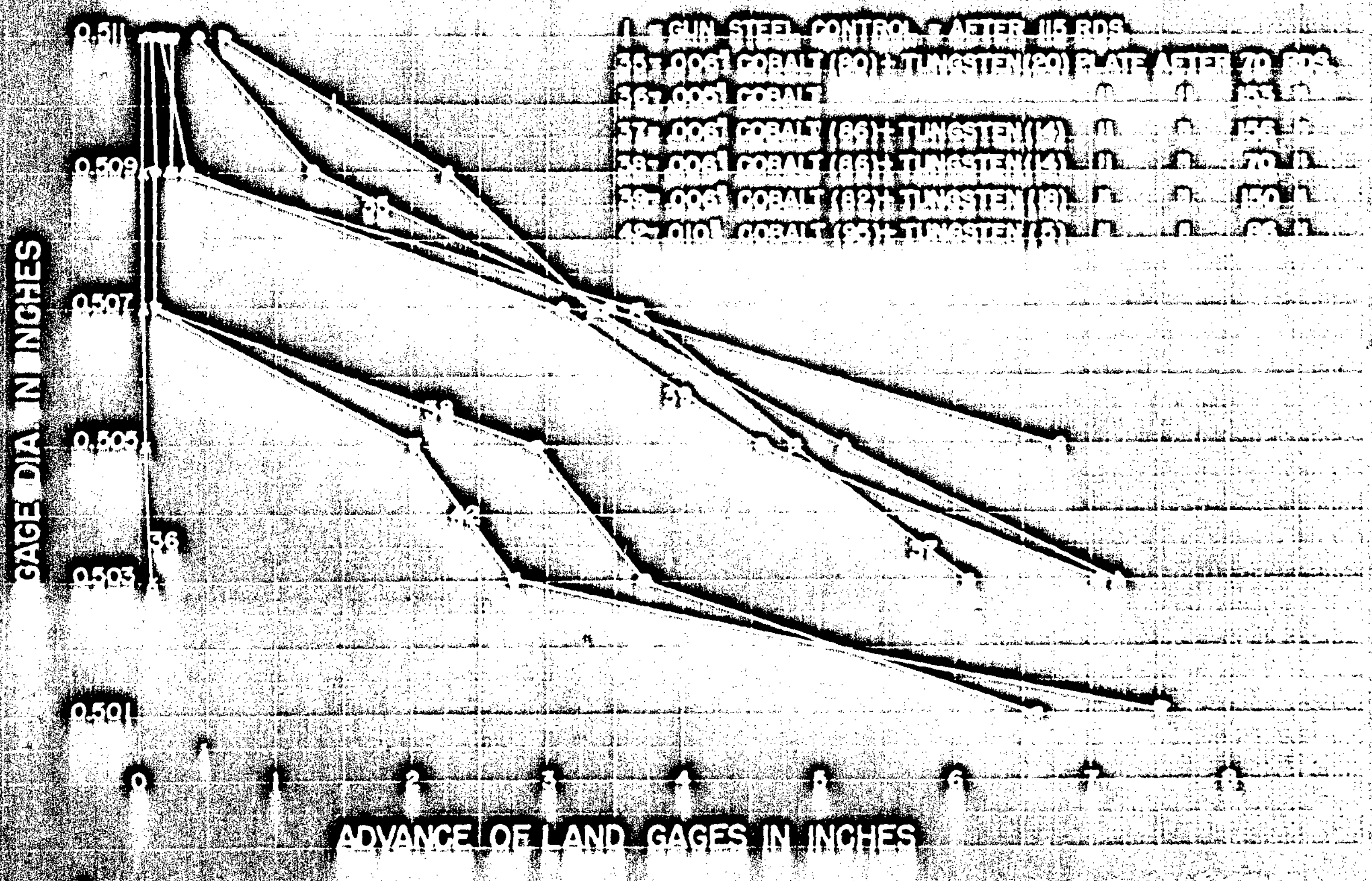
(b) Heat Treatment of the Cobalt-Tungsten Plate

Two heat treated cobalt-tungsten plates were tested (Tests J-F35 and J-F38). The test data showed no improvement in the heat treated plates.

(3) Conclusions

Cobalt and cobalt-tungsten alloy plates are not suitable for protection of a gun steel surface under hypervelocity conditions.

FIG.27-COMPARISON OF LAND EROSION OF COBALT AND COBALT ALLOY PLATES



3. Nickel-Tungsten Alloy Plates

The electroplating of the liners described in this section was done at the National Bureau of Standards. The conditions and details of the plating procedure may be obtained from the Bureau of Standards Reports.

(a) Erosion Resistant Properties of Nickel-Tungsten Alloy Plates

The melting point of nickel (1452°C) is too low to have good erosion resistant properties in a hypervelocity gun. The nickel-tungsten alloys have a slightly higher melting point but at the same time the thermal conductivity is reduced.

(1) Types of Failures Observed

The failure observed in the testing of the nickel-tungsten plated liners may be attributed to:

Low Melting Point. All liners failed due to poor resistant to gas erosion (melting of the surface).

(b) Erosion Tests on Nickel-Tungsten Plated Liners

(1) Variables Tested. The following variable was tested in the firings outlined below:

(a) Heat Treatment of the Plate

One plated liner (Test J-F33) was heated at 600°C for 1 hour in Vacuo in order to increase the hardness of the plate.

(2) Summary of Results

Table XVI gives a list of the nickel-tungsten alloy plates. A comparison of the advance of the land plug gages for the nickel-tungsten plated liners and the control gun steel liner is shown in Fig. 28.

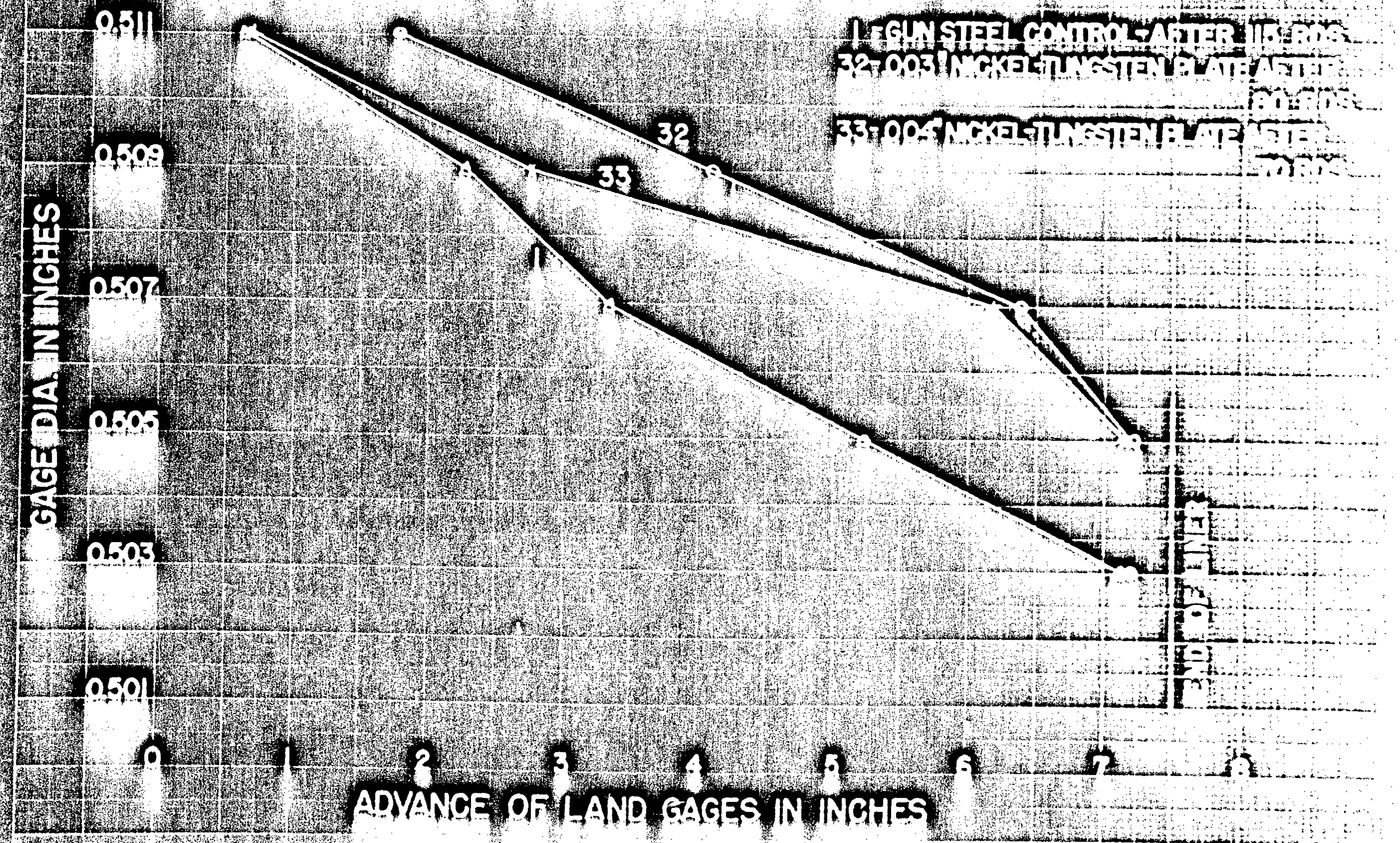


FIG.28 - COMPARISON OF LAND EROSION OF NICKEL ALLOY PLATES

CONFIDENTIAL

TABLE XVI - SUMMARY OF FIRING TESTS ON NICKEL ALLOY PLATED LINERS

F = Failure S = Satisfactory

Test	Plate	Thickness	Bullet	Powder	Rds. Fired	Extent of Failure	Advance of 0.505" Land Gage	Gas Erosion
J(F32)	75% Ni + 25% W	.0052"	B.M2	D.B.	80	100% off Lands and Grooves	+7.1"	F
J(F33)	75% Ni + 25% W(1)	.0042"	B.M2	D.B.	70	100% off Lands and Grooves	+7.1"	F

(1) Plating heated at 600°C for 1 hour.

CONFIDENTIAL

17-13

The details of each firing test are given in the Appendix (page 143). A summary of the results of the two tests is as follows:

(a) Composition and Heat Treatment

Two liners were tested having a composition approximately 75% nickel and 25% tungsten.

One liner was tested as plated and the second liner was heated at 600°C for one hour in Vacuo to harden the plate.

The data from these tests show:

(1) Both plates were severely eroded for the full length of the liner. Practically 100% of the plate was melted from the surface.

(2) Heat treatment of the plate gave no better performance.

(3) Conclusions

Nickel-tungsten alloy plates do not have the proper thermal properties to resist gas erosion under hypervelocity conditions.

4. Duplex Plates.

The electroplating of the liners described in this section was done at the National Bureau of Standards. The conditions and details of the plating procedure may be obtained from the Bureau of Standards report.

(a) Erosion Resistant Properties of the Duplex Plates Tested. All the duplex plates tested have used chromium as the main plate to protect the gun steel against the thermal effects of the powder gases. Various secondary plates have been tried to correct the causes of failure of the chromium plate.

The various duplex plates and the function of the secondary plate are listed below.

(b) Erosion Tests on Duplex Plates.

(1) Variables Tested. The following variables were tested in the firing tests outlined below:

(a) Copper plate on thin chromium plate. The purpose of the copper plate was to fill the cracks in the chromium plate during the first round fired.

(b) Chromium plate on copper plate. The purpose of the copper plate was to seal the cracks extending through the chrome plate and prevent the powder gases from undercutting the chrome plate.

(c) Chromium plate on nickel plate. The purpose was the same as under (b).

(d) Chromium plate on nickel plate on copper plate. The purpose was the same as under (b) and (c).

(e) <u>Chromium plate on a silicon-chrome-copper alloy.</u> The purpose of this test was to determine the behavior of the chrome plate on a base which produced no altered layer.

(f) <u>Chromium plate on cobalt-tungsten plate.</u> The purpose was to improve the bond at the steel interface by increasing the ductility.

(g) <u>Chromium plate on cobalt plate.</u> The purpose was the same as under (f).

(2) <u>Summary of Results.</u> Table XVII gives a list of the duplex plates tested in this program. The details of each firing test are given in the Appendix (page 149).

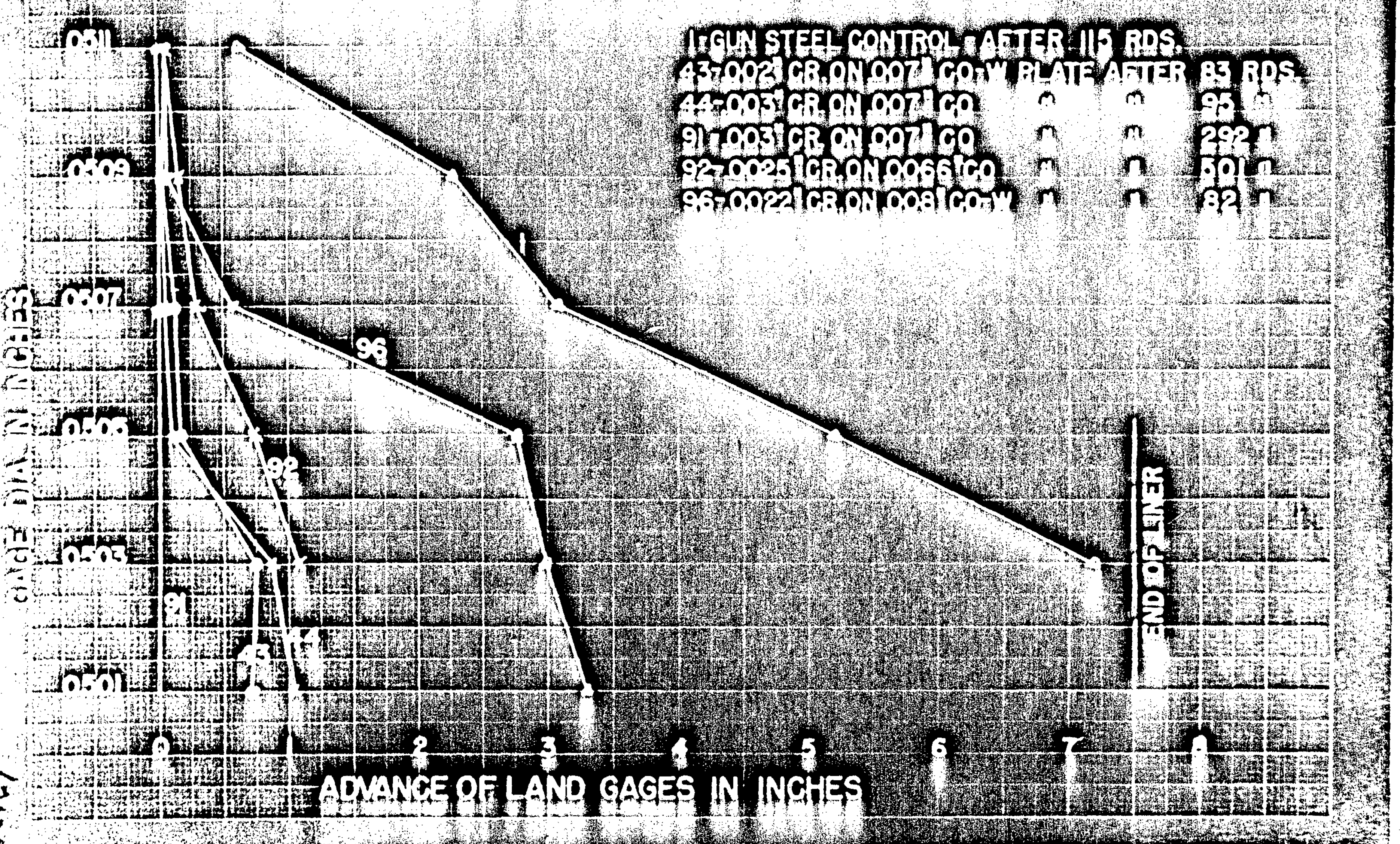
A comparison of the advance of the land plug gages for the cobalt-chromium duplex plated liners and the control gun steel liner is shown in Figure 29.

A summary of the results of the variables tested is as follows:

(a) <u>Copper plate on thin copper plate.</u> One liner was tested having 0.2 mil copper plate on 0.7 mil chromium plate. In 35 rounds the copper plate was completely removed and the chrome plate eroded at the O.R.

(b) <u>Chromium plate on copper plate.</u> One liner was tested having 1 mil chromium plate on 1 mil copper plate. In 80 rounds the chrome plate was removed from all the lands. The copper undercoat had been heated to a plastic state so that the stresses of the bullet had rubbed the chrome plate off all the lands. Examination of the plate adhering in the grooves showed that cracks in the chromium did not enter the underlying cooper plate which thus acted as a seal.

FIG.29-COMPARISON OF LAND EROSION OF DUPLEX PLATES



D-191

TABLE XVII. SUMMARY OF FIRING TESTS ON DUPLEX PLATED LINERS

F = Failure S = Satisfactory

Test	Plate	Bore Plate	Undercoat	Bullet	Powder	Rds. Fired	Extent of Failure	Advance of 0.505" Land Gage	Gas Erosion
J(F4)	Copper on Chromium	.0002" Cu	.0007" Cr	B.M2	D.B.	85	Copper removed – Cr plate off +1/4"	0.2"	F
J(F19)	Chromium on Copper	.001" Cr	.001" Cu	A.T.	D.B.	80	Cr plate off lands for full length of liner	0.496" = 5.8"	F
J(F21)	Chromium on Nickel	.001" Cr	.001" Ni	A.T.	D.B.	80	No plate removed beyond 2"	0.496" = 0.9"	S
J(F22)	Chromium on Nickel on Copper	.001" Cr	.001" Ni on .001" Cu	A.T.	D.B.	10	Plate removed for 1-1/2"	0.496" = 0.7"	S
J(F25)	Chromium	.005" Cr	Chrome Copper Alloy	P.E.	D.B.	80	Plate removed for 1/4"	0.496" = 0.05"	S
J(F45)	Chromium on Co-W Alloy	.002" Cr	.007" Co-W	B.M2	D.B.	85	Plate removed for 1/2"	0.2"	S
J(F44)	Chromium on Cobalt (1)	.003" Cr	.007" Co	B.M2	D.B.	95	No plate removed from bore surface	0.1"	S
J(F91)	Chromium on Cobalt	.0032" Cr	.0069" Co	B.M2	D.B.	292	Plate removed from lands for 1/8"	0	S

TABLE XVII (Continued)

Test	Plate	Bore Plate	Undercoat	Bullet	Powder	Rds. Fired	Extent of Failure	Advace of 0.505" Land Gage	Gas Erosion
J(F92)	Chromium on Cobalt (2)	.0025" Cr	.0086" Co	B-M2	D.B.	501	Plate removed from lands for 2"	0.75"	S
J(F96)	Chromium on Co-W Alloy (5)	.0022" Cr	.008" Co-W	B-M2	D.B.	82	Plate removed from lands for 4"	2.8"	S

(1) Swaging slight.

(2) Co plate heated at 900°C for 1 hour.

(5) Co-W alloy plate heated at 900°C fer 1 hour.

103-15

(c) Chromium plate on nickel plate. One liner was tested having 1 mil chromium plate on 1 mil nickel plate. In 30 rounds the plate was removed for a distance of 2 inches. It was found that the nickel becomes plastic in the same manner as the copper. The nickel plate differed notably from the copper plate in that it cracked around the crystal grains and admitted the gases to the underlying steel.

(d) Chromium plate on nickel plate on copper plate. One liner was tested having 1 mil chromium plate on 1 mil nickel plate on 1 mil copper plate. The behavior of this liner was the same as the liner under (c).

(e) Chromium plate on a silicon-chrome-copper alloy. One liner was tested having 5 mils chromium plate on a base which would not give an altered layer. However, the melting point and heat conductivity of the base metal was low with the result that melting or softening occurred at the chromium plate-copper alloy interface. Plate was removed from the bore surface for 1-1/2 inches during ten rounds fired.

(f) Chromium plate on cobalt-tungsten plate. Two liners were tested having 2 mils chromium plate on 7 and 8 mils cobalt-tungsten plate (Tests J(F43) and J(F96)). In Test J(F96) the cobalt-tungsten plate was heated at 900°C for one hour.

The results of the tests show

(1) The adhesion of the chrome plate to the cobalt-tungsten plate was poor in the heat treated liner.

(2) Poor local adherence of the cobalt-tungsten plate to the gun steel surface.

(3) Severe gas erosion of any exposed cobalt-tungsten plate.

(g) Chromium plate on cobalt plate. Three liners were tested having approximately 3 mils chromium plate on 7 mils cobalt plate (Tests J(F44), J(F91) and J(F92)). In Test J(F92) the cobalt plate was heated at 900°C for one hour.

The results of the tests show

(1) Excellent protection of the gun steel surface against powder gas erosion is obtained by a chromium-cobalt duplex plate.

(2) Swaging of the cobalt undercoat has been observed.

(3) The adhesion of the cobalt plate to gun steel and the chromium plate to the cobalt plate is good.

3. Conclusions.

(a) The chromium-cobalt-tungsten duplex plates do not give good performance under conditions of hypervelocity.

(b) The chromium-cobalt duplex plate offers promise in a hypervelocity gun using pre-engraved projectiles. The performance should be better than chromium plate alone.

(c) The chromium-cobalt duplex plate should give better performance than chromium plated muzzle sections in guns using molybdenum or chrome base alloy liners.

5. Molybdenum Plate

The plating from the vapor phase of the gun steel and Stellite #21 liners described in this section was done at the Bell Telephone Laboratories under Contract OEMsr-1124. The conditions and details of the plating procedure may be obtained from the Bell Telephone Laboratories report.

(a) Erosion Resistant Properties of Molybdenum Plate

The high melting point and excellent chemical properties of Molybdenum should make an ideal plate to protect a gun steel or a stellite surface. The molybdenum is plated on the bore surface from molybdenum carbonyl vapor under carefully controlled conditions. Under conditions of heat molybdenum can react with other elements to produce brittle intermetallic compounds. The formation of these brittle intermetallic compounds has been the principal cause of the failure of the molybdenum plate on gun steel and stellite surfaces.

(1) Types of Failure.

The type of failure observed in Mo plated liners may be attributed to:

Formation of Intermetallic Compounds, at the molybdenum-liner metal interface, thereby weakening the bond of the Mo to the liner metal and causing the metal to flake off the surface.

Low Coefficient of Expansion. The large difference in the coefficient of expansion between molybdenum and stellite or gun steel produces large stresses at the interface during firing.

These stresses together with the weakened bond caused by the formation of intermetallic compounds accelerate the failure of the molybdenum plate.

The types of failure observed in the Mo plated gun steel and stellite liners can be grouped as follows:

(a) Flaking of the Mo Plate from Surface:

In all liners tested, the Mo plate failed in this manner. The manner in which the plate failed was the same in all liners: namely - (1) the formation of a dark area; (2) blistering of this dark area; (3) cracks radiating from the center of the blister; (4) complete removal of the plate from the blistered area; (5) undercutting of the plate starting from the exposed gun steel or stellite. With double base powder the exposed stellite eroded faster than gun steel and produced deep scoring in the stellite base.

(b) Erosion Tests on Molybdenum Plated Gun Steel Liners

(1) Variables Tested. The following variables were tested in the firing tests given in Table XVIII.

(a) Type of Molybdenum plate - hard and soft

(b) Thickness of plate

(c) Different metals at the Mo interface

(d) Decarburization of the gun steel surface

(e) Type of powder

(2) Firing Schedule.

In the early tests, Schedule II with double base powder was followed. Failure occurred in such a short number of rounds fired, a less severe firing schedule was adopted for the Mo plated liners. Schedule V is as follows:

127-13

Schedule V

	Pressure (p.s.i. Cu)	Velocity (f.p.s.)
5 rounds - 300 grain charge	25000 - 30000	2600 - 2800
5 rounds - 350 grain charge	35000 - 40000	3000 - 3100
5 rounds - 400 grain charge	40000 - 46000	3200 - 3300
5 rounds - 450 grain charge	49000 - 55000	3350 - 3500
10 rounds - 450-476 grain charge	56000 - 58000	3600 - 3700
- - - - - - - - - -		
60 rounds - Erosion at established charge		
10 rounds - Pressure change		
- - - - - - - - - -		
130 rounds - Erosion at established charge		
10 rounds - Pressure change		
- - - - - - - - - -		

Borescope examination of the surface was made after each 5 round group, and after 30, 100 and 240 rounds.

Gage measurements were made after 100 and 240 rounds.

(3) Summary of Results.

Table XVIII gives a list of the Molybdenum plated gun steel liners tested in this program, showing the principal variables in each test. The details of each firing test are given in the Appendix, (page 153).

A summary of the results of the variables tested is as follows:

CONFIDENTIAL

TABLE XVIII. SUMMARY OF FIRING TESTS ON MOLYBDENUM PLATED GUN STEEL LINERS

Test	Mo Liner	Plate Thickness Mils	Type Plate	Metal at Mo Interface	Metal at Steel Interface	Powder	Rds. Fired	Remarks
J(F25)	97G	2.5	Hard	Steel	Mo	D.B.	80	Smooth bore
J(F26)	98G	3.8	Hard	Steel	Mo	D.B.	80	Smooth bore.
J(F28)	108G	3.2	Hard	Steel	Mo	D.B.	70	Smooth bore.
J(F54)	512	5	Hard	Steel	Mo	IMR	30	-
J(F75)	356	5	Soft	Steel	Mo	IMR	100	-
J(F78)	360	5	Soft	Steel	Mo	IMR	100	Steel surface decarburized
J(F80)	365	5	Soft	0.1 mil Cobalt	Co	IMR	240	-
J(F88)	373	5	Soft	0.1 mil Nickel	Ni	IMR	30	-
J(F89)	374	5	Soft	0.5 mil Cobalt	Co	IMR	100	-
J(F90)	375	1	Soft	0.5 mil Cobalt	Co	IMR	100	-
J(F95)	376	5	Soft	0.5 mil Nickel	Ni	IMR	100	-
J(F97)	380	5	Soft	0.1 mil Platinum	0.1 mil Cobalt	IMR	30	-
J(F105)	395	10	Soft	Steel	Mo	D.B.	100	-

Ball M-2 bullets were used in all the firings.

CONFIDENTIAL

109-13

(a) Type of Molybdenum Plate

Two types of molybdenum plate were tested: (1) The hard type produced by plating with 2% water vapor in the carbon monoxide - molybdenum carbonyl mixture, and, (2) the soft type, produced by plating with 10% water vapor in the mixture. A comparison of tests J(F54) and J(F75) shows that the soft type plate adheres to the surface for a greater number of rounds than the hard type plate.

(b) Thickness of Molybdenum Plate

Since the plate failure due to the formation of intermetallic compounds is caused by the thermal affects at the interface, the thickness of the plate should determine the behavior of the plate in firing. Molybdenum plate thickness was varied from 2.5 mils to 10 mils. A comparison of tests J(F25), J(F75) and J(F105) showed practically no improvement with the 10 mil coating. Severe failure of the plate occurred in 100 rounds with double base powder.

(c) Different Metals at Molybdenum Interface

Different metals were electroplated on the steel surface in an attempt to prevent the formation of the brittle intermetallic compounds. The thickness of the "sandwiching" metal varied from 0.1 mil to 0.5 mil. The following metals were tried: (1) cobalt, (2) nickel, (3) platinum.

The best plate was 0.1 mil cobalt with 5 mils soft type molybdenum plate. However, severe failure occurred after 240 rounds with IMR powder.

CONFIDENTIAL

TABLE XIX - SUMMARY OF RESULTS ON MOLYBDENUM PLATED GUN STEEL LINERS

Test	Mo Liner	Plate Condition After: 30 Rds.	Plate Condition After: 100 Rds.	ΔP - Pressure Change After 100 Rds.	ΔL and ΔG After 100 Rds. At 1" beyond O.R.: ΔL (.001")	ΔL and ΔG After 100 Rds. At 1" beyond O.R.: ΔG (.001")
J(F25)	97G	-	80 Rds. = Several large areas of plate removed.	-	-	-
J(F26)	98G	-	80 Rds. = 90% of plate removed.	-	-	-
J(F28)	106G	-	70 Rds. = Several small areas of plate removed.	-	-	-
J(F54)	312	75% of plate removed O.R. to 4".	-	-	-	-
J(F75)	356	Small areas of plate removed.	95% plate removed from O.R. to 4".	-9100	+3.0	7.6
J(F78)	360	Plate off edge of bullet seat.	90% plate off 2 grooves.	-2000	-0.6	+3.8
J(F80)	365	No change.	Small areas of plate removed.	100 Rds. = +1300 240 Rds. = +3300	-0.6	-1.2
J(F88)	373	Plate off one land from O.R. to 4".	-	-	-	-
J(F89)	374	Small areas off bullet seat.	50% plate removed from 4" to 8" beyond O.R.	+400	-0.2	-0.3

CONFIDENTIAL

TABLE XIX (Continued)

Test	Mo Liner	Plate Condition After 50 Rds.	Plate Condition After 100 Rds.	ΔP - Pressure Change After 100 Rds.	ΔL and ΔC After 100 Rds. At 1" beyond O.R. ΔL (.001")	ΔL and ΔC After 100 Rds. At 1" beyond O.R. ΔC (.001")
J(F90)	375	Plate off edge of bullet seat.	Large number of small areas removed.	+2200	+0.6	-0.4
J(F93)	376	Plate off 2 grooves from O.R. to 1-1/2"	50% plate removed from O.R. to 4".	- 100	-0.2	+4.8
J(F97)	380	50% plate removed from O.R.	-	-	-	-
J(F105)	395	Plate off edge of bullet seat.	90% plate removed from O.R. to 4".	-18400	22.3	22.0

119-12

(d) Decarburization of the Gun Steel Surface.

A gun steel liner was plated with molybdenum after removing most of the carbon from the bore surface. A comparison between tests J(F54) and J(F73) showed little improvement in the adherence of the molybdenum plate.

(e) Type of Powder.

The molybdenum plates were tested with two types of powder; namely, (1) IMR type, flame temperature 2940°K and (2) double base containing 20% nitroglycerin, flame temperature 3560°K.

The higher potential powder produced the most severe failure and also caused failure in the smallest number of rounds.

A summary of the results of the molybdenum plated gun steel liners is given in Table XIX.

(c) Erosion Tests on Molybdenum Plated Stellite Liners.

(1) Variables Tested. The following variables were tested in the tests given in Table XIX.

(a) Type of molybdenum plate

(b) Bonding temperature

(c) Thickness of plate

(d) Type of powder

(2) Firing Schedule.

Schedule V was followed using IMR powder for the less severe schedule and double base powder for the more severe schedule.

(3) Summary of Results.

Table XX gives a list of the molybdenum plated stellite liners tested in this program, showing the principal variables in each test.

CONFIDENTIAL

TABLE XX - SUMMARY OF FIRING TESTS ON MOLYBDENUM PLATED STELLITE LINERS

Test	Mo Liner	Plate Thickness Mils	Type Plate	Bonding Temperature	Powder	Rds. Fired	Remarks
J(F48)	271	5	Hard	625°C to 900°C/10 min.	D.B.	87	-
J(F49)	285	1.5		"	D.B.	6	-
J(F50)	290	1.5	"	"	IMR	14	-
J(F51)	292	5	"	"	IMR	66	Trouble in plating procedure
J(F52)	295	5	"	"	IMR	14	" " " "
J(F53)	307	5	"	"	IMR	40	De-gassed at 1000°C for 10 min. before plating.
J(F55)	315	5	"	625°C/15 min.	IMR	90	-
J(F57)	338	4.7	"	"	IMR	250	-
J(F58)	348	5	"	"	IMR	100	-
J(F59)	349	5	Soft	"	IMR	240	-
J(F74)	353	5	"	"	D.B.	100	-
J(F76)	357	5	Hard	700°C/10 min.	IMR	100	-
J(F77)	362	5	"	780°C/10 min.	"	100	-
J(F81)	366	5	Soft	700°C/10 min.	"	100	-
J(F82)	367	5	"	"	"	240	-
J(F83)	368	7	"	"	"	240	-
J(F85)	369	5	Hard	550°C/10 min.	"	240	-
J(F86)	372	7	Soft	625°C/10 min.	"	240	-
J(F94)	378	7	"	550°C/10 min.	"	50	Trouble in plating procedure
J(F95)	379	7	"	"	D.B.	240	-
J(F105)	393	8	"	600°C/10 min.	"	240	-
J(F107)	397	10	"	"	"	240	-
J(F108)	399	10	"	"	"	100	-
J(F109)	404	10	"	"	"	100	-
J(F110)	405	12.5	"	"	"	240	-

CONFIDENTIAL

The details of each firing test are given in the Appendix (page 159).

A summary of the results of the variables tested is as follows:

(a) Type of Molybdenum Plate.

Two types of molybdenum plate were tested: (1) the hard type, produced by plating with 2% water vapor in the carbon monoxide-molybdenum carbonyl mixture and (2) the soft type, produced by plating with 10% water vapor in the mixture. A comparison of tests J(F58) and J(F59) shows that the soft type plate adhere to the surface for a greater number of rounds than the hard type plate.

(b) Bonding Temperature.

The initial molybdenum plate was bonded at four different temperatures; (1) 550°C, (2) 625°C, (3) 700°C and (4) 780°C and then followed with a 5 mil coating of molybdenum plate.

A comparison of tests J(F85), J(F57), J(F58), J(F76) and J(F77) showed that the lower the bonding temperature the better the performance. The most severe failure occurred in the liner bonded at 780°C, and there was very little difference in the behavior of the liners bonded at 550°C and 625°C.

(c) Thickness of Molybdenum Plate.

The thickness of the molybdenum plate was varied from 1.5 mil to 12.5 mils. The performance of the molybdenum plate was a function of the plate thickness. However, the thicker plates were very rough and the rough spots were usually the starting points of plate failure.

The data on Table XXI show that a 12.5 mil coating will not protect the stellite surface against attack by double base powder.

(d) Types of Powder.

The molybdenum plates were tested with two types of powder; namely, (1) IMR type and (2) double base containing 20% nitroglycerin.

Stellite #21 alone is not eroded by IMR powder in the Caliber .50 Erosion Testing Gun. However, plate failure at the stellite-molybdenum interface occurred with IMR powder.

Stellite #21 alone is severely eroded by double base powder and the purpose of the molybdenum plate is to protect the stellite surface because of its high melting point. However, in all liners tested, from the thinnest (1.5 mil) to the thickest (12.5 mil) coatings, failure at the stellite-molybdenum interface occurred with double base powder.

The exposed stellite was then severely eroded and scored by the double base powder.

Because of the higher temperatures at the bore surface, failure with double base powder occurred in a few number of rounds than with the IMR powder.

A summary of the results on the molybdenum plated stellite liners is given in Table XXI.

3. Conclusions.

Molybdenum plates on gun steel and stellite fail by a weakening of the bond at the molybdenum interface. This is caused by a thermal reaction producing brittle intermetallic compounds. For this reason

CONFIDENTIAL

TABLE XXI - SUMMARY OF RESULTS ON MOLYBDENUM PLATED STELLITE LINERS

Test	Mo Liner	Conditions of Plate After 100 Rds.	Conditions of Plate After 240 Rds.	ΔP-Pressure Change After 100 Rds.	ΔP-Pressure Change After 240 Rds.	ΔL at 1/4" beyond O.R. in .001" 100 Rds.	ΔL 240 Rds.	ΔG at 1/4" beyond O.R. in .001" 100 Rds.	ΔG 240 Rds.
J(F48)	271	87 Rds. = 75% plate removed from surface.	-	87 Rds. = -14700	-	87 Rds. = +15.6	-	87 Rds. = +1.3	-
J(F49)	285	6 Rds. = Large areas plate removed.	-	-	-	-	-	-	-
J(F50)	290	14 Rds. = Small areas plate removed.	-	-	-	-	-	-	-
J(F51)	292	86 Rds. = Small areas plate removed.	-	85 Rds. = -1975	-	86 Rds. = +2.2	-	86 Rds. = +2.7	-
J(F52)	295	14 Rds. = Small areas plate removed.	-	-	-	-	-	-	-
J(F53)	307	40 Rds. = 90% plate off O.R.	-	-	-	40 Rds. = +4.2	-	-	-
J(F55)	315	Small areas removed from O.R. to 1".	-	-5400	-	90 Rds. = +4.4	-	90 Rds. = +1.6	-
J(F57)	338	Small areas removed from lands at 2"	Plate off lands from O.R. to 1-7/8".	-2500	-7200	+4.3	+4.3	+2.7	+2.3

CONFIDENTIAL

117-A

CONFIDENTIAL

TABLE XXI (Continued)

Test	Mo Liner	Conditions of Plate After 100 Rds.	Conditions of Plate After 240 Rds.	ΔP-Pressure Change After 100 Rds.	ΔP-Pressure Change After 240 Rds.	ΔL and ΔC at 1/4" beyond O.R. in .001" ΔL 100 Rds.	ΔL 240 Rds.	ΔC 100 Rds.	ΔC 240 Rds.
J(F58)	343	Large areas off lands & grooves.	-	-4900	-	+2.6	-	+9.4	-
J(F59)	349	No change	Small areas off lands & grooves.	- 300	-5000	+3.5	+3.1	+2.2	+1.2
J(F74)	353	Large areas off lands & grooves.	-	-13300	-	+9.5	-	+3.6	-
J(F76)	357	Plate off edges of lands.	-	-5300	-	+1.5	-	-0.2	-
J(F77)	362	Plate off lands from O.R. to 1".	-	-9800	-	+11.3	-	+0.5	-
J(F81)	366	Plate off lands from O.R. to 3/8".	-	-3400	-	+1.7	-	+0.6	-
J(F82)	367	Plate off lands from O.R. to 3/8".	Plate off lands from O.R. to 3/4"	-3500	-11600	+3.3	+10.2	-0.1	+0.1
J(F83)	368	Plate off edges of lands at O.R.	Plate off edges of all lands.	- 300	-2100	+0.5	+ 0.4	+0.0	-0.4
J(F85)	369	Plate off edge of lands at O.R.	Small areas off grooves from O.R. to 1-1/2".	+ 600	-3800	+0.5	+ 0.7	+1.1	+0.6
J(F88)	372	No change.	Small areas off grooves from O.R. to 1/4".	-2300	-2300	+0.7	- 0.2	-1.1	-1.0

CONFIDENTIAL

118-19

CONFIDENTIAL

TABLE XXI (Continued)

Test	Mo Liner	Conditions of Plate After 100 Rds.	Conditions of Plate After 240 Rds.	ΔP-Pressure Change After 100 Rds.	ΔP-Pressure Change After 240 Rds.	ΔL and ΔC at 1/4" beyond O.R. in .001" ΔL 100 Rds.	ΔL 240 Rds.	ΔC 100 Rds.	ΔC 240 Rds.
J(F94)	378	Failure in plating technique		-	-	-	-	-	-
J(F95)	379	Plate off lands at 1/4" beyond O.R.	Plate off all lands for 1".	+3800	-11200	+1.2	+15.2	+2.0	+10.0
J(F105)	393	Plate off grooves for 3 inches.	Plate off all grooves and partially from lands.	+5900	-7100	-0.6	+13.3	-0.3	+13.5
J(F107)	397	Plate off edge of bullet seat.	90% Plate off lands and grooves at O.R.	-700	-8200	+0.5	+3.9	+2.2	-1.2
J(F108)	399	Plate off grooves for 1/2 inch.	-	-3600	-	-0.2	-	+10.1	-
J(F109	404	75% Plate off grooves for 4".	-	-4800	-	+2.3	-	+9.7	-
J(F110)	405	Small areas off grooves at 1/4".	Large areas off lands & grooves for 4 inches.	+1100	-3400	+5.5	+2.4	+3.1	-0.2

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molybdenum plates do not afford protection for the gun steel and stellite surfaces under conditions of hypervelocity.

4. Metallographic Examination.

Sections of the fired liners were sent to Harvard University and the Bell Telephone Laboratories for metallographic examination.

The results of these examinations may be obtained from the Harvard Report on "Metallographic Examination of Gun Liners and Coatings Tested under Hypervelocity Conditions", and from the Bell Telephone Laboratories Report on "Molybdenum Plating from the Vapor Phase".

130.3

6. Sprayed Molybdenum Coatings.

The molybdenum coated liners described in this section were prepared at the Massachusetts Institute of Technology under Contract OEM-sr 608. The details of the spraying procedure are described in their reports.

(a) Erosion Resistant Properties of Sprayed Molybdenum.

The high melting point of molybdenum and its excellent erosion resistant properties made it desirable to develop a process of applying a thin coating (.020" to .050" thick) to a gun bore surface.

The low coefficient of expansion, the low ductility and brittleness of the unworked molybdenum and the reactivity at the molybdenum-gun steel interface to form intermetallic compounds are properties working against the success of this project.

(b) Erosion Tests on Sprayed Molybdenum Liners.

(1) Variables Tested. The following variable was tested in the firings listed below:

(a) Composition.

Three liners were tested having the following compositions:

(i) Pure molybdenum

(ii) Molybdenum containing 1/2% nickel

(iii) Molybdenum containing 1/2% nickel and 5% copper.

(2) Summary of Results.

The details of each firing test are given in the Appendix (page 169). A summary of the results of the three liners is as follows:

(a) All the sprayed molybdenum coatings failed by cracking due to lack of ductility and the failure of the molybdenum to follow the expansion of the steel liner during firing.

(3) Conclusions.

Sprayed molybdenum coatings showed no promise of success and the development was not carried any further under Contract OEM-sr 608.

112-12

7. Parco Lubrite Coatings

A gun steel barrel (45 inch length) was sent to the Parker Rust Proof Company of Detroit and the bore was coated with a Parco Lubrite coating approximately 0.5 mil thick. The Parco Lubrizing process converts the steel surface into a non-metallic oil-absorptive film consisting chiefly of a mixture of iron and manganese phosphates. It was believed that the reduced friction between the bore and the projectile would result in an increased velocity life of the barrel.

A comparison shown on Table XXII of the erosion of the lands and grooves with an uncoated gun steel barrel showed no improvement in the performance of the Parco Lubrized bore.

Table XXII Comparison Between Parco-Lubrized Gun Steel and Plain Gun Steel

Test	Surface	Powder	Bullet	ΔP After 145 Rds.-psi.	ΔV After 145 Rds.-fps.
C(F6)-C(F12)	Gun Steel Control	D.B.	A.T.	-13200	-340
J(F45)	Parco-Lubrized	D.B.	A.T.	-15000	-360

183-13

8. Fluorocarbon Films

In order to determine the effect of a film of fluorocarbon on erosion a special type of bullet (BC-2) with grooved base-cup sealing ring was used. This groove, together with a deep groove in front of the base-cup, was filled with fluorocarbon before seating the bullet with the expectation that when fired the bullet would receive sufficient lubrication to permit an increase in velocity. After firing J(F1), the bullet seat and the origin of rifling were found to be covered with a film of fluorocarbon which helped to seal erosion cracks and thus reduced the drop in muzzle velocity as expected, but the degree of erosion was just as severe as that of the gun steel control.

The fluorocarbon film was supplied by Division 8, NDRC.

9. Oxidized Gun Steel

Two short pieces cut from a Browning machine gun were sent to the Taft-Peirce Manufacturing Company, Woonsocket, Rhode Island, for application of a special oxidized surface of magnetic oxide of iron. The method of forming this surface is by means of rapid oxidation at a temperature of about 1000°F. in steam, which produces a smooth black appearance. After firing these liners (J(F5)) a total of 70 rounds it was concluded that the special oxidizing treatment of the bore surface did not increase the life of the barrel under hypervelocity conditions.

10. Metallographic Examination of Fired Liners and Coatings.

Contract OEM-sr 537 at Harvard University was inaugurated for the primary purpose of providing facilities for the metallographic examination of specimens of various materials fired in the Erosion Testing Gun at the Franklin Institute. Fired liners and barrels described in this report were sent, therefore, to Harvard for metallographic examination.

A complete report of these examinations will be found in their report on "Metallographic Examination of Gun Liners and Coatings Tested under Hyper-velocity Conditions".

The Franklin Institute takes this opportunity to express profound appreciation to Mr. Hobstetter for the tremendous assistance that he and his associates have provided in this work.

APPENDIX

The following data have been abstracted from progress reports of the Franklin Institute (Contract OEMsr 533). It should be noted that these firings were all made in the caliber .50 Erosion Testing Gun under hyper-velocity conditions as defined early in this report (except where special attention is called to the contrary).

Part I. Control Tests on Gun Steel

E(F3): Monobloc Gun Steel Barrel. 478 grains Double Base powder. Ball M-2 bullets. Rate of fire 3.3 R.P.M. 115 rounds fired. Firing schedule I.

(1) The advance of the plug gages with number of rounds fired is given in Table 1.

(2) The change in pressure and velocity with number of rounds is given in Table 2.

(3) Examination of recovered bullets indicated excessive wear on one side. This condition increased with number of rounds fired until the engraving extended far down on the boat-tail of the Ball M-2 bullet with no wear on the opposite side. This means that the bullet was balloting down the bore.

(4) Accuracy measurements were made by means of a screen 45 ft. from the muzzle. Tipping and keyholing occurred to some extent before round 20, but after this the keyholes produced a wider dispersion which increased to the end of the test. Hence, under these conditions the erosion test should be limited to 20 rounds.

E(F4): Monobloc Gun Steel. 473 grains Double Base powder. Ball M-2 bullets. 115 rounds fired. Conditions the same as in E(F3). Firing schedule I.

(1) Borescope examination showed that both progression and extent of erosion were the same as that in E(F3).

(2) A comparison of the advance of land gages in E(F3) and E(F4) is given in Table 1 below:

Table 1 - Advance of Land Gages in E(F3) and E(F4)

	After 35 Rounds		After 70 Rounds		After 115 Rounds	
Gage	E(F3)	E(F4)	E(F3)	E(F4)	E(F3)	E(F4)
0.5011	8.31"	8.13"	10.75"	9.94"	13.23"	13.40"
0.5031	4.56	3.93	7.08	7.18	10.30	10.55
0.5050	2.03	1.73	5.99	5.20	8.17	8.33
0.5088	0.74	0.59	4.13	3.35	6.83	6.74
0.5091	0.23	0.11	1.08	2.26	5.36	5.24
0.5112	0.20	0.28	0.31	0.60	3.80	3.39
0.5122	-	0.30	-	0.55	-	2.23

(3) A comparison of pressure change and of velocity change with progress of erosion is given in Table 2 below:

Table 2. - Pressure Change (psi.Cu) and Velocity Change (fps.)

	After 35 Rounds		After 70 Rounds		After 115 Rounds	
Drop	E(F3)	E(F4)	E(F3)	E(F4)	E(F3)	E(F4)
ΔP	-6770	-7240	-7750	-12710	-8850	-15840
ΔV	- 173	- 108	- 259	- 266	- 210	- 288

(4) Accuracy patterns and bullet performance were identical with those in E(F3).

C(F6): Monobloc Gun Steel. Double Base powder. A.T. bullets. Lands 0.010" high. 150 rounds fired. Firing schedule II.

127

(1) 70 rounds. The O.R. showed characteristic rounding of the forcing cone and the lands, also thermal cracking of the bore surface tapering off toward the muzzle. Coppering was heavy in the grooves 20" - 32" beyond the O.R.

(2) 150 rounds. The forcing cone and the lands at the O.R. were very badly eroded, less toward the muzzle. Coppering occurred 28" - 38" from the O.R. Erosion of the lands at the O.R. was twice that of the grooves. The increase in the land diameter 0.5" beyond the O.R. was 0.024". ΔV = -320 f.p.s. ΔP = -15,400 p.s.i. ΔV = -200 f.p.s. at the end of 90 rounds.

(3) Recovered bullet #138 showed heavy engraving on the bourrelet and the body, which would cause excessive wear of the lands.

(4) The accuracy pattern had a mean radius of dispersion at 100 ft. between rounds (11-65) = 2.35", between rounds (81-135) = 3.3".

C(F12): Monobloc Gun Steel. 476 grains Double Base powder. A.T. bullets. 224 rounds fired. Firing schedule II.

Results of this test do not differ significantly from those in C(F6).

L1(F5): Monobloc Gun Steel. Lands 0.010" high, .50 twist. Double Base powder. P.E. bullets. 290 rounds fired. Firing schedule II.

(1) Thermal cracking at the O.R. was severe, diminishing toward the muzzle. After 70 rounds it extended only 10" from the O.R., but after 290 rounds it extended 28".

(2) Between rounds 140 and 210 engagement of the bullet with the O.R. was lost. This made the bullets skid and cause excessive wear on the lands.

(3) Erosion of the lands took place slowly at first, rapidly between rounds 140 - 210, and then more slowly again. Erosion of the grooves had the same characteristics.

(4) The velocity drop at the end of the test was -284 f.p.s. Since it is often considered that the useful life of a gun ends when the velocity drop reaches -200 f.p.s., it was calculated that this condition was reached after 210 rounds as compared with 85 rounds for artillery bullets. Hence, the velocity life is increased 2-1/2 times by the use of P.T. bullets.

(5) Bullets recovered up to round 140 were normal, those recovered during rounds 208 - 210 showed double engraving and marks of skidding. Bullets recovered during rounds 278 - 280 showed no double engraving, hence engagement with the O.R. must have been completely lost with the result that the emerging bullets failed to have the proper spin.

(6) The accuracy life was determined as about 250 rounds from the appearance of 9 yawing and keyholing bullets which passed through the screen during rounds 221 - 275. With artillery bullets the accuracy pattern is bad at 150 rounds.

L1(F9): Monobloc Gun Steel. Lands 0.010" high. Double Base powder. 580 rounds fired. Firing schedule II.

(1) Erosion at the O.R. was characteristic of double base powder. Thermal cracking was less toward the muzzle, increasing with number of rounds. The lands were worn smooth by skidding bullets from 9" beyond the O.R. to the muzzle.

(2) Removal of steel from the O.R. with P.E. bullets was about half that with A.T. bullets.

(3) Pressure change after 360 rounds was -9,600 p.s.i., and the velocity change was -310 f.p.s. A change of velocity of -200 f.p.s. occurred after 267 rounds.

(4) Accuracy. The mean radius of dispersion was constant to rounds 275 = 1.1", between rounds (291-345) = 3.2", also in the latter range keyholing began.

(5) Recovered bullets were unchanged to round 214. They were double engraved after round 280 but no change in accuracy resulted. About the same round meshing of the bullet with the rifling was lost.

130-14

Part II. Liners

1. MOLYBDENUM LINERS:

E(F5): Molybdenum tube #A-376. Ball M2 bullets - Two warm-up rounds fired with IMR powder at diminished load, then full load of D.B. powder - 24 rounds fired.

A section examined at the Geophysical Laboratory showed the metal free from flaws but the grain size was not uniform. There was a very coarse columnar structure on the outside changing to a fine grain size at center, each about half the thickness of tube. There was no distortion of the grains parallel to the axis. Yield point in compression parallel to axis = 47,000 lb. per square inch. Hardness in the longitudinal direction = 91.5 Rockwell B, in the radial direction = 89.6 Rockwell B.

(1) Neither thermal cracking nor powder gas erosion was shown in the borescope examination. There was no visible gas erosion after 24 rounds.

(2) The liner cracked after one round at diminished pressure.

(3) The liner lacked strength and ductility to withstand pressures at unsupported areas. Ultimate failure occurred at keyways after 24 rounds at 58,000 psi.

E(F6): Molybdenum tube #A-384. One round was fired with IMR powder at diminished load - 1 round fired.

This tube was examined at the Geophysical Laboratory and found to be fine grained.

(1) The liner cracked longitudinally in several places so badly that further firings were impossible.

(2) Further testing of molybdenum tubes is to be done with smooth bore until conditions are found which enable molybdenum to stand the shock of firing.

E(F7): Molybdenum Liner #(B-16-4). Smooth bore, drilled and reamed from molybdenum rod. Shrunk into heated breech section. 5 rounds fired.

During an attempt at insertion the liner brake. The final liner 4-1/2" long was inserted and fired. After removal of the breech section the liner broke into several pieces.

(1) Longitudinal cracking occurred after 1 round at a pressure of only 10,000 psi.

(2) Cracking increased till one piece was ready to be lifted out after 5 rounds, hence firing was terminated.

(3) There was no evidence of thermal cracking or of gas erosion.

(4) Molybdenum lacks the strength to withstand the shock of firing.

E(F10): Molybdenum Liner. Smooth bore. Single base powder used throughout. Reduced charge, 250 - 476 grains. Pressure varied from 12,000 to 46,300 psi. Ball M2 bullets. 9 rounds fired.

(1) The liner cracked on the 4th round at a pressure of 38,500 psi.(Cu).

(2) After 9 rounds, examination of the sectioned liner showed four longitudinal cracks running the full length of the liner.

E(F11): Molybdenum Liner. Swaged, smooth bore. Double base powder. Reduced charge. Pressure gradually increased from 11,000 to 57,000 psi. Ball M2 bullets. 46 rounds fired.

This swaged molybdenum liner was shrunk cold under a pressure of 20,000 psi. into a tapered steel liner. It was hoped this method of shrinking molybdenum into the steel liner would give no unsupported areas back of the molybdenum. The work was done by the Crane Company, Chicago, under Contract OEMsr-629.

(1) Several longitudinal cracks developed during the 7th round at a pressure of 45,200 psi.

(2) Since it can be assumed the method of mounting the liner gave it good support, the cracking must be attributed to an inherent lack of ductility and resistance to impact present in thick molybdenum sections.

(3) Both gage measurements and microscopic examination showed the molybdenum to be chemically inert to the powder gases of the double base powder.

E(F12): Molybdenum Liner. 2-stave, smooth bore. Reduced charge (10 rounds) increasing to standard charge (140 rounds). Ball M2 bullets. 150 rounds fired. Firing Schedule II.

(1) Gage measurements indicated no wear.

(2) The surface showed no signs of either thermal cracking or erosion.

(3) Tests should be made of a segmented liner that is rifled.

E(F16): Molybdenum Liner. 10-stave, rifled with lands 0.005" high. 460 grains D.B. powder. Ball M2 bullets. 150 rounds fired. Firing Schedule II.

The liner of commercial molybdenum was composed of 10 segments made from 3/8" swaged molybdenum rod. After being machined into a tapered liner it was press fitted into a steel carrier under a load of 10,000 lb. It was not brazed.

(1) Flattening of the lands at the O.R. due to engraving stresses, and filling of the partially opened seams with copper began after a few rounds.

(2) After 150 rounds the lands did not reach their full height for 1.5" from the O.R., and copper filled the open seams right down to the steel carrier.

(3) There was a drop in pressure of 1945 psi.(Cu) due to flattening of the lands which reduced the initial forcing pressure.

(4) The molybdenum surface showed no signs of thermal erosion.

E(F17): Molybdenum Liner. 10-stave, smooth bore. Ball M2 bullets. 150 rounds fired. Firing Schedule II.

The same (E(F16)) type of molybdenum rod was used in making this tapered 10-segmented liner which was first brazed into a dummy carrier. Then, with segments brazed together, the liner was finish-machined and brazed into the carrier, which was heat-treated and finished after brazing. The brazing alloy used, of copper, nickel and silicon, had a melting point of about 1100°C.

(1) After 70 rounds the joints between the segments had opened slightly, and in several places part of the brazing material had been removed.

(2) After 150 rounds the joints had not opened any further, but in several places molybdenum had been chipped from the edges of the segments.

(3) The molybdenum surface showed evidence of neither thermal cracking nor powder gas erosion.

(4) Gage measurements indicated no loss of metal from the bore surface. The smooth bore offered no forcing resistance to the ball M2 bullets, hence there was practically no bullet wear on the molybdenum surface.

E(F18): Molybdenum Liner. 2 stave. Rifled, lands 0.005" high. 476 grains D.B. powder. Ball M2 bullets. 70 rounds fired. Firing Schedule II.

The strips were made from standard molybdenum about 3/16" thick. The liner was a press fit in the steel carrier.

(1) Seams between the segments opened up and were filled with gilding metal from the bullet jacket.

(2) Three cracks developed in the area of the O.R.

(3) A section of molybdenum surface was torn from the area of the bullet seat.

(4) Lands at the O.R. were flattened for 1/8" due to swaging.

(5) There were no signs of thermal erosion on either land or groove surface.

(6) Removal of metal from the lands was small and from the grooves was zero.

E(F19): Molybdenum Liner. 2-stave. Rifled, lands 0.005" high. 476 grains D.B. powder. P.E. bullets. 150 rounds fired.

(1) After 150 rounds the seams between the two segments were tight at the O.R. and opened slightly at the muzzle end of the liner. Their condition was much better than in E(F18) where ball M2 bullets were used. Hence engraving stresses probably are an important factor in causing the seams of these segmented liners to open up.

(2) Gage measurements showed no wear on either land or groove surface.

(3) After 150 rounds the pressure drop was negligible and the velocity drop was 60 fps. Under the same conditions the velocity drop in a gun steel liner is 150 fps.

(4) There were no signs of powder gas erosion.

E(F21): Molybdenum Liner WMT-1F. Incast. Rifled, lands 0.005" high. 476 grains D.B. powder. Ball M2 bullets. 10 rounds fired.

The liner material was made from a 3/4" swaged pure molybdenum rod "incast" in steel. The molybdenum was made by commercial procedures at Bloomfield, N.J., while the "incasting" was done at the Crane Company, Chicago. The steel used in the casting was air hardened and tempered to the hardness of gun steel. The breech section was assembled at Franklin Institute.

(1) The molybdemum cracked badly the full length of the liner. Two small sections caved in due to lack of a proper backing for the molybdenum tube.

(2) The failure was caused by lack of ductility and inability to follow the expansion of the steel backing as well as faulty casting.

B6-13

E(F24): (90% Mo + 10% W) alloy liner MW-1-1. 2 Staves. Rifled, lands 0.005" high. Ball M2 bullets. 150 rounds fired. Firing Schedule II.

Inside diameter and joint surfaces were machined in a shaper using a formed tool. With halves clamped on a mandrel the outside was ground, after which the halves were reshaped to remove distortion set up in the roughing operation. Then the joining surfaces were lapped and the halves held in position by means of a collet chuck while the internal diameter was ground. The taper of 1/32" per foot was ground on the outside diameter and the liner pressed into the carrier with a drift of 3/4". After lapping to finish size, the liner was rifled.

The hardness data obtained by Climax Molybdenum Company are reported in Table II.

(1) When examined at the end of 72 rounds cracks were observed which increased progressively to the end of the test. Each segment developed cracks which ran the full length of the liner.

(2) The seams opened up and were filled with copper on the lands.

(3) Slight swaging of the lands occurred at the O.R. but not beyond.

(4) After 72 rounds portions of the alloy surface were broken and this condition grew worse thereafter.

(5) The drop in pressure, due to swaging of the lands at the O.R., increased from 3700 psi. after 72 rounds to 40000 psi. after 152 rounds.

E(F25): (85% Mo + 15% W) alloy liner WAH-4F. 2 Staves. Rifled, lands 0.005" high. Rounds 17 - 26 were fired at the rate of 6 rounds per minute, the others at 4 rounds per minute. Ball M2 bullets. 146 rounds fired. Firing Schedule II.

The alloy was made into 3/4" sintered billets at Bloomfield by Process B. The billets were forged into 3/4" rods and die-troughed at East Pittsburgh at 1450°C. The rest of the fabrication was carried out in the same manner as that described above (E(F24)). The Westinghouse Company reported that the micro-examination of this liner showed a crystal structure much more favorable than that of the previous liner (E(F24)).

The hardness data obtained by Climax Molybdenum Company are reported in Table II.

(1) After 16 rounds the liner was cracked and the surface showed moderately severe spalling.

(2) After 76 rounds there was neither visible erosion nor swaging of the lands.

(3) After 146 rounds the liner broke up, the metal coming off in layers, so that only half of the liner remained in the gun, thus making further measurements impossible.

(4) The drop in pressure after 76 rounds was only 300 psi.(Cu).

E(F26): (80% Mo + 20% W) alloy liner WAH-5F. 2 Staves. Rifled, lands 0.005" high. Reduced charge D.B. powder for 4 rounds. Ball M2 bullets. 72 rounds fired. Firing Schedule II.

The method of manufacture and assembly was the same as in E(F25). However, the drift of WAH-5F was only 1/2" since the liner bent during the pressing operation and would not enter further.

The hardness data obtained by Climax Molybdenum Company are reported in Table II.

(1) After 12 rounds the liner cracked, metal being removed from the surface in layers due, probably, to its lamellar structure.

(2) After 72 rounds the liner broke up and half of it was blown out of the gun, rendering further measurements impossible.

E(F33): Molybdenum Liner. F.I.45-1. 2-stave. Rifled, lands 0.010" high. 476 grains D.B. powder. 2 groups of 70 rounds each at 4 rounds per minute followed by 2 groups of 140 rounds at 6 rounds per minute. Steel banded P.E. bullets. 454 rounds fired.

Mo powder was hydrostatically pressed in a rubber mold to eliminate internal cracks produced when a steel mold was used.

(1) The bore surface showed no evidence of any attack by powder gases.

(2) There was slight checkerwork cracking in the grooves. Beyond 4" from the O.R. there were two cracks which started from the seams.

(3) Swaging at the O.R. was slight and, 6" beyond, the driving edge of the lands was perceptibly worn.

(4) A comparison of the advance of the gages on the lands and the drop in velocity and in pressure compared with those in control test L1(F5) is given in Table 5 below.

Table 8 - Comparison of Test E(F33) with Control Test L1(F5)

Gage Diameter	L1(F5) 220 Rds.	E(F33) 454 Rds.
0.492"	>23"	-0.38"
0.494	>23	-0.03
0.496	>23	-0.01
0.498	>23	0
0.500	+21.0	0

Drop	L1(F5) 285 Rds.	E(F33) 285 Rds.	E(F33) 454 Rds.
ΔV	- 278	- 65	- 165
ΔP	-7800	-500	-3950

(5) Failure occurred on the lands where the seam between the 2 staves crossed the lands. At this point the lands were broken away due to impact with the bullet.

(6) If the staves were so designed that the seam followed in the grooves this type of failure might be eliminated.

E(F36): Mo Liner (N-15). Molybdenum + 0.05% Nickel

Firing Conditions. 476 grains Double Base (20% N.G.) powder. Ball M-2. Firing Schedule III. Fired 309 rounds.

Liner. Helical, two-staves. Taper 1/32"/ft. - outside diameter at large end 0.690". Bore diameter 0.500".

Results. Staves were cracked longitudinally in middle of each groove--did not interfere with the firing. End of stave beneath cartridge case was cracked.

Lands were swaged at the origin of rifling.

Liner moved forward, opening rear joint beneath cartridge case. Plastic flow of metal in muzzle area produced a constriction.

The test was concluded because of difficult case extraction caused by the opening of the rear joint beneath the cartridge case.

1-0-10

E(F38): Mo Liner (W-16). Molybdenum + 0.01% Nickel.

Firing Conditions. 372 grains of Double Base (40% N.G.) powder. Ball M-2 bullets. Firing Schedule III. Fired 119 rounds.

Liner. Helical, two-staves. Taper 1/32"/ft. - outside diameter at large end 0.720". Bore diameter 0.500".

Results. Staves were cracked longitudinally in middle of each groove--did not interfere with firing. There was moderate swaging of the lands at O.R. The rear joint beneath the cartridge case opened up due to liner having moved forward. The seams between the staves were in good condition.

The test was concluded because of the difficult case extraction caused by the opening of the rear joint beneath the cartridge case.

E(F39): Mo Liner (W-17). Pure Molybdenum.

Firing Conditions. 365 grains of Double Base (40% N.G.) powder. Pre-engraved steel bullets. Firing schedule III. Fired 294 rounds.

Liner. Helical, two-staves. Taper 1/32"/ft. - outside diameter at large end 0.722". Bore diameter 0.490".

Results. Staves cracked longitudinally down center of the groove --did not interfere with firing. There was measurable swaging of the lands for the first inch. Seams were in good condition. Forward movement of the liner opened up rear joint #1 by 0.03" to .04" and produced a constricted bore at the muzzle end of the liner. This condition stopped the test because of difficult case extraction.

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E(F40): Mo Liner (N-18-1). 85% Molybdenum + 15% Tungsten.

Firing Conditions. 365 grains of Double Base (40% N.G.) powder. Pre-engraved steel bullets. Firing Schedule III. Fired 146 rounds.

Liner. Helical, flanged, two-Staves. Shoulder 3/4" long. x 1/32" face. Taper 1/32"/ft. Bore diameter 0.490".

Results. Staves cracked longitudinally down the center of the grooves—did not interfere with firing. Each stave cracked circumferentially beyond the flanged area. There was measurable swaging of the lands for the first inch.

The flange on the Mo stave liner prevented the rear joint #1 beneath the cartridge case from opening up. However, the same forces cracked the Mo staves beyond the flange and the liner moved forward in this area, causing the cracks to open up about .03" and .05" and a constriction of the bore at the muzzle end of the liner. For this reason the test was concluded.

E(F41): Mo Liner (N-18-2). 85% Molybdenum + 15% Tungsten.

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule III. Fired 432 rounds.

Liner. Helical, flanged, two-staves. Straight shoulder 3/4" long. x 1/32" face. Taper 1/32"/ft. Bore diameter 0.500".

Results. The flange prevented rear Joint #1 from opening up. The staves cracked radially beyond the flange—opening more with firing and causing constriction at the muzzle end. Staves cracked longitudinally down center of the grooves—did not interfere with firing.

Some slight breaking away of the metal at the edge of the seams.

The test was stopped because of the constriction at the muzzle end.

147-B

E(F42): Mo Liner (W-16-2). Molybdenum + .01% Ni.

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule III. Fired 148 rounds.

Liner. Helical, two-staves, cold twisted. Shoulder 3/4" long. x 1/32" face. Taper 1/32"/ft. Bore diameter 0.500".

Results. Longitudinal and diagonal cracking occurred in first pressure round. During the 130 round burst the liner cracked badly at 2 to 2-1/2" from the breech end and the forward parts of the 2 staves were blown out the muzzle. Severe constriction at breech end of liner. The liner failed by cracking, warping of the staves and complete breaking up of the forward end of the liner.

E(F43): Mo Liner (W-16-3). Molybdenum + .01% Ni.

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. Firing schedule III. Fired 155 rounds.

Liner. Four-staves, straight seams, integral shoulder, Shoulder 3/4" long x 1/32" face. Taper 1/32"/ft. on diameter. Cold press fit - interference .0015" on diameter. Bore diameter 0.500".

Results. Each stave cracked longitudinally, usually in center of each groove. Severe surface spalling of metal along seams at the muzzle end and where lands cross the seams. Slight swaging of the lands at O.R. Rear joint beneath case remained tight. There was severe constriction at muzzle end. Test was concluded because of severe spalling along seams.

E(F44): Mo Liner BL-23. Molybdenum + .08% Ni.

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. Firing schedule III. Fired 166 rounds.

Liner. Helical, two-staves, integral shoulder. Shoulder 3/4" long x 1/32" face. Taper 1/32"/ft. Cold pressed with .0015" interference on diameter. Bore diameter 0.500".

Results. Slight swaging of lands at O.R. Staves cracked circumferentially at the end of the shoulder. Continued firing opened this crack. The liner twisted during firing so the rifling was out of line with the rifling in the muzzle section. Test was concluded because of severe circumferential cracking.

E(F45): Mo Liner (N-16-4). Molybdenum + .01% Ni.

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullet. Firing schedule III. Fired 293 rounds.

Liner. Precision twisted, Helical, four-staves, integral shoulder. Shoulder 3/4" long x 1/32" face. Taper 1/32"/ft. Press fit - .002" interference. Bore diameter 0.500".

Results. The staves were cracked longitudinally down the center of the grooves. There was surface spalling from the edge of the bullet seat to the origin of rifling on two of the four staves. There was slight flattening of the lands at the O.R. Test was concluded because of fracture and spalling of the surface at the bullet seat and origin of rifling.

4-13

E(F47): Mo Liner IL 33-3. (Mo + 0.1% Co)

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. (Cd. plated for 573 rounds, regular bullets for remainder of test). Firing schedule III. Fired 1133 rounds.

Liner. Straight seams, two-staves with integral shoulder. Taper 1/32"/ft. Shoulder 3/4" long x 1/32" face. Shrink fit - .003" interference on diameter. Bore diameter 0.500".

Results. There was slight checkerwork cracking in the bullet seat area. There was longitudinal cracking in the grooves. Swaging of the lands increased as the firing increased. Swaging and tearing of small pieces of Mo from the surface occurred where the lands crossed the straight seams. There was gradual movement of metal toward the muzzle end of the liner.

The following tables shows the advance of the Land Gages and Groove Gages.

Advance of Land Gages

Gage Diameter	After 153 Rds.	293 Rds.	573 Rds.	1133 Rds.
0.503"	+0.07"	+0.05"	+0.23"	+1.50"
0.505	0.03	0.05	0.13	0.60
0.507	0.01	0.01	0.04	0.10
0.509	-0.01	-0.01	0	0
0.511	-0.25	-0.31	-0.20	-0.19

Advance of Groove Gages

Gage Diameter	After 153 Rds.	293 Rds.	573 Rds.	1133 Rds.
0.513"	-0.01"	-0.01"	0	+0.04"
0.515	0	0	+0.01"	0.01
0.517	0	0	0	0.01
0.519	0	0	0	0.01
0.521	0	0	0	0

The following table shows the pressure change. P_o = 56400 psi.(Cu).

	After 153 Rds.	293 Rds.	573 Rds.	1133 Rds.
ΔP	+1700 psi.	+2500 psi.	+2300 psi.	+3300 psi.

Test was concluded because of the constriction of the bore.

E(F48): Mo Liner BL-33-4. (Mo + 0.1% Co).

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullet. Firing schedule III. Fired 152 rounds.

Liner. Straight seams, two staves with integral shoulder. Taper 1/32"/ft. Shoulder 3/4" long x 1/32" face. Shrink fit - .003" interference on diameter. Bore diameter 0.500".

Results. There was slight swaging of the lands at the origin of rifling. Surface spalling was greatest at 4" to 8" beyond O.R. and was more severe on one of the staves. The test was concluded because of severe spalling of the metal along the seams.

Failure was due to poor microstructure of Mo.

E(F49): Mo Liner BL-33-5. (Mo + 0.1% Co).

Firing Conditions. 476 grains of Double Base (20% N.C.) powder. Ball M-2 bullet. Firing schedule III. Fired 2022 rounds.

Liner. Helical, two-staves. Shoulder 3/4" long x 1/32" face. Taper 1/32"/ft. Shrink fit - .004" interference on diameter. Bore diameter 0.500".

Results. Examination of the fired liner showed (1) slight cracking longitudinally, (2) pronounced pattern of checker-work cracking on the

1.1-13

bore surface, (3) slight spalling occurred along the edges of the seams at the muzzle end of the liner, (4) swaging of the lands at O.R. and (5) the rear joint beneath the cartridge case opened slightly.

The following table show the advance of the Land Gages and of the Groove Gages.

Advance of Land Gages

Gage Diameter	After 151	291	571	1131	1411	2022 Rds.
0.503"	0.05"	0.09"	0.16"	0.75"	1.29"	2.96"
0.505	0.02	0.03	0.05	0.11	0.17	2.15
0.507	0.02	0.01	0.02	0.04	0.03	0.17
0.509	0	-0.04	-0.14	-0.15	-0.16	-0.04
0.511	-0.25	-0.32	-0.30	-0.23	-0.22	-0.15

Advance of Groove Gages

Gage Diameter	After 151	291	571	1131	1411	2022 Rds.
0.513	0	-0.01"	0	+0.08"	-0.12"	+0.16"
0.515	0	0	+0.01"	0.02	-0.03	0.14
0.517	0	0	0.01	0.02	-0.02	0.09
0.519	0	0	0.01	0.01	-0.01	0.03
0.521	0	0	0.01	0.01	-0.01	0.01

The following table shows the pressure change. P_o = 55,800 psi.(Cu).

	After 151	291	571	1131	1411	2022 Rds.
ΔP	+1000 psi.	+1800	+400	+1300	0	-4200

The test was concluded because the increased land diameter at O.R. (due to swaging) and partly due to the badly eroded muzzle section caused the 4200 psi. pressure drop.

147

E(F50): Mo Liner IL-33-7. (Mo + 0.1%).

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullet. Firing schedule III. Fired 2024 rounds.

Liner. Helical, two-staves. Shoulder 3/4" long x 1/32" face. No taper on body of liner. Shrink fit - .004" interference on diameter. Bore diameter 0.500".

Results. The performance of this liner was practically the same as Mo Liner BL-33-5 (Test E(F49).

The taper on the body of the liner is only necessary for ease of insertion of the liner in the carrier.

The following tables show the advance of the Land Gages and of the Groove Gages.

Advance of Land Gages

Gage Diameter	After 154	294	574	1134	1414	2024 Rds.
0.503"	0.06"	0.17"	0.42"	1.29"	1.74"	2.48"
0.505	0.03	0.07	0.10	0.47	1.27	1.86
0.507	0.01	0.02	0.03	0.09	0.24	1.27
0.509	0	0	-0.01	0.01	0.04	0.10
0.511	-0.04	-0.05	-0.08	-0.02	0	0.02

Advance of Groove Gages

Gage Diameter	After 154	294	574	1134	1414	2024 Rds.
0.513"	—	—	-2.07"	-5.82"	-2.23"	-2.17"
0.515	—	+0.08"	-7.43	-7.41	-6.62	-6.34
0.517	-0.01"	0	0	0	+0.04	+0.17
0.519	0	0	-0.01	0	+0.01	+0.04
0.521	0	0	-0.01	0	0	+0.02

The following table shows the pressure change P_0 = 56,600 psi.(Cu).

155-11

	After 154	294	574	1134	1414	2024 Rds.
ΔP	+600 psi.	+400	-1300	0	-4600	-14200*

* Most of this drop was due to a badly eroded muzzle section.

E(F51): Mo Liner BL-36-1. (Mo + 0.1% Co).

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Parco Lubrized Steel Pre-engraved bullets. Firing Schedule III. Fired 442 rounds.

Liner. Two-staves, straight seams, integral shoulder. Shoulder 3/4" long x 1/32" face. Taper 1/32"/ft. Shrink fit - .003" interference on diameter. Bore diameter 0.490".

Results. Examination of the fired liner showed (1) slight swaging of the lands at O.R., (2) slight longitudinal cracking in the grooves, (3) slight surface checkerwork cracking, (4) slight surface spalling of metal occurred where the lands crossed the seams, (5) the rear joint beneath the cartridge case opened slightly, and (6) constriction in the bullet seat, probably due to slight warping of stave. This condition caused the failure of the liner.

E(F53): Mo Liner BL-37-1. (Mo + 0.1% Co)

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Parco Lubrized steel pre-engraved bullets. Firing schedule IV. Fired 1052 rounds.

Liner. Helical, two-staves, integral shoulder. Shoulder 3/4" long x .0185" face. Taper 1/32"/ft. Shrink fit - .003" on diameter. Bore diameter 0.490".

Results. Examination of the fired liner showed (1) slight longitudinal cracking in the grooves, (2) surface checkerwork cracking, and (3) severe spalling occurred from 4" to 8" beyond O.R.—this condition caused the failure of the liner.

E(F54: Mo Liner BL-36-2. (Mo + 0.1% Co).

Firing conditions. 476 grains of Double Base (20% N.G.) powder. Parco Lubrized steel pre-engraved bullets. Fired 4 rounds.

Liner. Helical, two-staves, integral shoulder. Shoulder 3/4" long x 1/32" face. Taper 1/32"/ft. Shrink fit - .003" interference on diameter. Bore diameter 0.490".

Results. Failure occurred on the fourth pressure round due to blowing out of liner beneath the cartridge case neck. This was caused by an unsupported area in the region of the liner shoulder.

E(F55): Mo Liner BL-35. (Mo + 0.1% Co)

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. Fired 77 rounds.

Liner. Helical, two-staves, integral shoulder. Shoulder 3/4" long x 1/32" face. Taper 1/32"/ft. Shrink fit - .003" interference on diameter. Bore diameter 0.500".

Results. Examination of the fired liner showed (1) slight longitudinal cracking in the grooves, (2) slight spalling along the edge of the seams, and (3) constriction at both the breech end and muzzle end of the liner. This condition caused failure of the liner.

E(F56): Mo Liner BL-38. (Pure Mo).

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. Firing schedule IV. Fired 905 rounds.

Liner. Helical, two-staves. Shoulder 3/4" long x 1/32" face. Taper 1/32" face. Taper 1/32"/ft. Shrink fit - .003" interference on diameter. Bore diameter 0.500".

Results. Examination of the fired liner showed: (1) staves were cracked longitudinally in the grooves, (2) slight checkerwork cracking of the grooves, (3) moderate spalling of the metal along the edge of the seam from 5" to 7" beyond the O.R., (4) the rear joint opened slightly, and (5) severe swaging of the lands for a distance of 4 inches - this condition caused the failure.

E(F57): Mo Liner BL-39-1. (Pure Mo).

Firing Conditions. 476 grains of Double Base (20% N.G.) powder. Ball M-2 bullets. Firing schedule IV. Fired 785 rounds.

Liner. Helical, two-staves, no shoulder. Taper 1/32"/ft. Shrink fit - .003" interference on diameter. Bore diameter 0.500".

Results. Examination of the fired liner showed: (1) staves were cracked longitudinally in the grooves, (2) circumferential cracking at +1" beyond O.R., (3) pronounced checkerwork cracking of the bore surface, and (4) slight progressive swaging of the lands at O.R.

The liner failed because the rear joint beneath the cartridge case opened up and prevented extraction of the cases. Severe constriction at the muzzle end of the liner occurred.

2. CHROME BASE ALLOY LINERS:

E(F29): Liner (CX-5). 60 Cr - 25 Fe - 15 W alloy.

Firing Conditions. 440 grains D. B. powder (20% N.G.). Ball M-2 bullets. Firing schedule II. Fired 85 rounds.

Liner. 0.500" bore.

Results. Examination of the fired liner showed: (1) longitudinal cracking, (2) network cracking on bore surface and pitting of surface, (3) constriction of bore, due to volume change in Cr-base alloy. Test was concluded because of longitudinal cracking of liner, and also because of volume changes resulting in excessive high pressures.

E(F30): Liner (CX-6). 50 Cr - 45 Fe - 5 Mo alloy.

Firing Conditions. 465 grains D. B. powder (20% N.G.). Ball M-2 bullets. Firing schedule II. Fired 84 rounds.

Liner. 0.500" bore.

Results. Examination of the fired liner showed: (1) longitudinal cracking, (2) constriction of grooves due to volume changes, (3) network cracking of surface and pitting of surface. Liner failed because of (1) longitudinal cracking, (2) drop in pressure and velocity due to removal of metal from O.R. indicating softening of metal, also (3) constriction of groove diameter.

E(F31): Liner (CX-10). 60 Cr - 25 Fe - 15 Mo alloy.

Firing Conditions. 460 grains D. B. (20% N.G.) powder. Ball M-2 bullets. Firing schedule II. Fired 309 rounds.

Liner. 0.500" bore.

152-13

Results. Examination of the fired liner showed: (1) longitudinal cracking, and (2) surface pitting.

Test was concluded due to (1) drop of pressure and velocity caused by escape of gases through deep longitudinal cracks, and (2) longitudinal cracking and pitting.

E(F46). Liner (CX-30). 60 Cr - 30 Fe - 10 Mo alloy.

Firing Conditions. 476 grains D. B. (20% N.G.) powder. Ball M-2 bullets. Firing schedule III. Fired 151 rounds.

Liner. 0.500" bore. Intermediate tube and liner, both alloys of 60 Cr - 30 Fe - 10 Mo., shrink-fitted into assembly with 0.001" diametrical interference.

Results. Examination of the fired liner showed: (1) longitudinal cracking, (2) checkerwork cracking of bore surface, and (3) severe pitting of surface due to intercrystalline cracking.

Test was concluded because of (1) longitudinal cracking, allowing powder gases to escape, and (2) severe pitting of the surface.

E(F52). Liner (CX-34). 60 Cr - 25 Fe - 15 Mo alloy.

Firing Conditions. 405 grains D. B. (20% N.G.) powder. Ball M-2 bullets. Firing schedule III. Total rounds fired 568.

Liner. 0.500" bore shrink-fitted into assembly with 0.001" diametrical interference. Inner tube under high compressive stresses.

Results. Examination of the fired liner showed: (1) surface cracking, (2) pitting, (3) constriction of bore.

Test was concluded due to (1) excessive pressures caused by constriction and roughened surface.

E(F58). Liner (OX-35). 60 Cr - 25 Fe - 15 Mo alloy.

Firing Conditions. 450 grains D. B. (20% N.G.) powder. Ball M-2 bullets. Firing schedule IV. Total rounds fired 110.

Liner. 0.500" bore, shrink-fitted into steel carrier, 0.005" diametrical interference. Two-staves, straight seams.

Results. Examination of the fired liner showed: (1) longitudinal and transverse cracking, (2) severe pitting of surface, (3) large blow hole at 1/2" to 1" beyond O.R.

Test was concluded due to severe longitudinal and transverse cracking.

3. <u>TANTALUM LINERS</u>:

<u>E(F14)</u>: <u>Tantalum, Smooth bore</u>.

<u>Firing Conditions</u>. Gradually increasing loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing schedule II. Fired 150 rounds.

<u>Liner</u>. .040" thick. Pressed in steel tube. Bore diameter 0.5103".

<u>Results</u>. Examination of the fired liner showed: (1) no thermal cracking; (2) no fracture of any kind; and (3) surface appeared to be roughened, probably by the wear of the bullet on the Tantalum surface.

<u>E(F20)</u>: <u>Tantalum rifled</u>.

<u>Firing Conditions</u>. Gradually increasing loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing schedule II. Fired 150 rounds.

<u>Liner</u>. Hardened to about 52 R_c Liner, 8", .045" thick. Pressed in a steel carrier. Bore diameter 0.500".

<u>Results</u>. Examination of the fired liner showed: (1) pressure drop of 3,875 p.s.i.; (2) groove surface showed no signs of thermal cracking; (3) lands failed slightly due to removal of metal by friction; (4) Tantalum surface appeared to be drawn; and (5) showed longitudinal tear cracks.

155-13

4. STELLITE LINERS:

E(F22): Liner Stellite #22.

Firing Conditions. 476 grains D.B. (20% N.C.) powder. Ball M-2 bullets. Firing schedule II. Total rounds fired 85.

Liner. 0.500" bore. Stellite #22 liner 1/8" thick.

Results. Examination of the fired liner showed: (1) Lands completely eroded away for 5" beyond O.R.; (2) Driving edge eroded for entire length of liner; (3) Network of cracks on land and groove surface for entire length.

Failure due to large pressure drop caused by melting of the stellite surface.

E(F23): Liner Stellite #22.

Check test of E(F22) with similar results. Test was abandoned after 25 rounds.

E(F27): Liner Stellite #21.

Firing Conditions. 476 grains D.B. (20% N.C.) powder. Ball M-2 bullets. Firing schedule II. Total rounds fired 85.

Liner. 0.500" bore, Stellite #21 liner 1/8" thick.

Results. Examination of the liner after firing showed: (1) Lands badly eroded up to 3.5 inches beyond O.R.; (2) Driving edge of lands badly eroded to 6" beyond O.R.; (3) Bore surface badly cracked throughout the length.

Failure of liner due to excessive drop in pressure and velocity caused by erosion of lands, due to melting and softening of the surface.

E(F28): Liner Stellite #21.

Firing Conditions. 476 grains IMR powder. Ball M-2 bullets. Firing schedule II. Total of 509 rounds fired.

Liner. 0.500" bore. Stellite #21 liner 1/8" thick.

Results. The following observations were made after firing: (1) No swaging or erosion of the lands; (2) Fine network of cracks on Stellite surface; (3) Gun steel at end of Stellite liner badly eroded causing velocity drop.

These results showed that the Stellite #21 was resistant to the action of the powder gases of IMR type powder at this rate of fire.

E(F34): Stellite #21 Liner.

Firing Conditions. 455 grains IMR powder, Ball M-2 bullets. Firing schedule III and 1-300 round group at 12 R.P.M. Total of 1582 rounds fired.

Liner. 0.500" bore. Stellit #21 liner 1/8" thick.

Results. The following observations were made after firing: (1) No swaging of the lands; (2) Slight rounding of the lands edges at O.R.; (3) Fine network of cracks on the Stellite surface; (4) Practically no advance of the land plug gages.

E(F35): Stellite #21 Liner.

Firing Conditions. 435 grains RDX powder, CR-1 type, Lot No. EX 6112. Ball M-2 bullets. Firing schedule III and 1-300 round group at 13 R.P.M. Total of 1023 rounds fired.

Liner. 0.500" bore. Stellite #21 liner 1/8" thick.

Results. The following observations were made after firing: (1) No swaging of the lands; (2) slight rounding of the lands at O.R.; (3) network of cracks on the stellite surface; (4) practically no advance of the land gages.

158-13

5. <u>NICKEL BASE ALLOY LINERS</u>:

<u>E(F-8)</u>: <u>Monel Metal Liner</u>.

<u>Firing Conditions</u>. 476 grains D.B. (20% N.C.) powder. Ball M-2 bullets. Firing schedule I. Total rounds fired 35.

<u>Liner</u>. 0.500" bore.

<u>Results</u>. Examination of the liner after firing showed: (1) fine checker-work cracks; (2) lands completely eroded away at O.R. and badly eroded beyond.

<u>E(F-9)</u>: <u>Z - Nickel Liner</u>.

<u>Firing Conditions</u>. 476 grains D.B. (20% N.C.) powder. Ball M-2 bullets. Firing schedule I. Total rounds fired 70.

<u>Liner</u>. 0.500" bore.

<u>Results</u>. The following observations were made of the liner after firing: (1) lands and grooves were pitted; (2) bullet seat area has fine checker-work cracking; (3) lands badly eroded at O.R.

<u>E(F13)</u>: <u>Zirconium-Nickel Liner</u>.

<u>Firing Conditions</u>. 476 grains D.B. (20% N.C.) powder. Ball M-2 bullets. Firing schedule I. Total rounds fired 45.

<u>Liner</u>. 0.500" bore.

<u>Results</u>. Examination of the fired liner showed: (1) severe swaging of the lands for 2" from O.R.; (2) thermal cracking in the grooves.

6. SILICON STEEL:

E(F15): Silicon Steel.

Firing Conditions. Gradually increasing loads of Double Base (20% N.C.) powder. Ball M-2 bullets. Fired 7 rounds.

Liner. 6" liner.

Results. Liner cracked badly in first 7 rounds due to the brittleness of the silicon steel.

Part III. Coatings and Electroplates

1. CHROME PLATED LINERS:

J(F3): Chromium plate 0.0007" thick. Steel surface machined. Rifled, lands 0.005" high. Liner in two sections, 4-1/2" and 3-1/2" respectively. Ends plated with copper 0.005" to 0.010" thick. D.B. powder. Ball M-2 bullets. 45 rounds fired.

The liners were plated at the Springfield Armory using the chromium plating technique developed there. The ends were plated with copper in order to act as a seal.

Results. (1) Chromium was removed from bullet seat, forcing cone and land surface. For 1/4" beyond the O.R. erosion by powder gases was severe, undercutting the grooves; (2) Chromium in the grooves was in good condition. Erosion beyond 1/2" from the O.R. on both lands and grooves was improved.

J(F6): Chromium plate (standard) 0.001" thick. Steel surface electropolished. Rifled, lands 0.005" high. D.B. powder. P.E. bullets. 115 rounds fired.

The liner was plated at Battelle Memorial Institute, Columbus, Ohio.

Results. (1) The erosion and flaking of the surface was much less than that obtained with Ball M-2 bullets (see J-F7); (2) The plate was off the bullet seat and the driving edge of the lands for about 1/8". The surface appeared wrinkled; (3) Elimination of engraving stresses increased the life of the chrome plated barrel.

J(F7): Chromium plate (standard), 0.001" thick. Steel surface electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 115 rounds fired.

The liner was plated as in J(F6).

Results. (1) The plate was removed completely from the bullet seat and from the lands for 3/16"; (2) The lands were eroded below the surface of the grooves some of which show undercutting of the plate; (3) The failure of the plate was similar to that of the Springfield chrome plate (see J-F3); (4) Localized engraving stresses are an important factor in the failure of chrome plate.

J(F8): Chromium plate (standard), 0.005" thick. Electropolished. Lands 0.005" high. D.B. powder. P.E. bullets. 115 rounds fired.

The liner was plated as in J(F6). Large clearances on the lands eliminated localized engraving stresses.

Results. (1) The plate showed a characteristic net-work of cracks, but there was neither land nor groove erosion; (2) There was no change in either the dimensions of recovered bullets or the accuracy pattern to the end of the test.

J(F9): Chromium plate, 0.001" thick. Machined surface. Lands 0.005" high. D.B. powder. Ball M-2 bullets. 115 rounds fired.

The chromium plate was applied to a machined gun steel surface by the Van der Horst Corporation, Olean, New York.

Results. (1) Erosion of the lands was greater and of the grooves the same as that of the Springfield plate and the Battelle plate as described above. This was probably due to poorer bonding of the plate to the steel surface beneath; (2) The chemical and the thermal resistance of the plate to the powder gases was the same.

J(F10): Chromium plate (standard), 0.001" thick. Bureau of Standards. Machined surface. Lands 0.005" high. D.B. powder. Ball M-2 bullets. 115 rounds fired.

Results. (1) Failure of the plate was similar to that of other chromium plated surfaces when Ball M-2 bullets and D.B. powder were used; (2) Cracking of the plate was less than that observed with an equal thickness plated at Battelle.

J(F11): Chromium plate (Low Contraction), 0.001" thick. Bureau of Standards. Machined surface. Lands 0.005" high. D.B. powder. Ball M-2 bullets. 115 rounds fired.

Results. (1) Failure of the L.C. plate at the O.R. was similar to that of the standard (H.C.) plate; (2) After 35 rounds the L.C. plate was in better condition than the H.C. plate at the same stage; (3) After 70 rounds the L.C. plate began to fail rapidly and at the end of the test it was in worse condition than the H.C. plate (J-F10).

J(F12): Chromium plate (standard), 0.001" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. P.E. bullets. 150 rounds fired.

Results. (1) Plate was worn off the driving edge of the lands for the full length of the liner and at the O.R. for 3/8" all over the lands and for 1/4" in the grooves; (2) Cracking was less than that observed with Battelle plate; (3) The plate removed was much less than when Ball M-2 bullets were used, (J-F10).

J(F13): Chromium plate (L.C.), 0.001" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. P.E. bullets. 150 rounds fired.

Results. (1) At the O.R., L.C. plate was off the lands for 1/4"; (2) At the O.R., L.C. plate was off the grooves for 1/8"; (3) L.C. was off the driving edge of the lands for 1.0"; (4) With P.E. bullets the L.C. plate suffers less erosion than the H.C. plate (See J-F12).

J(F14): Chromium plate (standard), 0.005" thick. Battelle. Electropolished. Lands 0.005" high. D.B. powder. Ball M-2 bullets. 115 rounds fired.

Results. (1) The plate was cracked and pitted in several places, but was adhering to lands and grooves and showing comparatively little failure; (2) There was very little difference between the erosion with Ball M-2 bullets in this test and that with P.E. bullets in Test J(F8); (3) The thickness of the chrome plate appears to be the main factor in obtaining protection of the bore surface of gun steel.

J(F15): Chromium plate (standard), 0.001" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. A.T. bullets. 150 rounds fired.

Results. (1) Plate was completely removed from the bore surface for 7/16" from O.R. Failure on the lands extended to 2-1/2" from O.R., and the removal of plate from the edges of the lands extended the full length of the liner; (2) Much more plate was removed in this test than in that where P.E. bullets were used (J-F12).

J(F16): Chromium plate (L.C.), 0.005" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. P.E. bullets. 440 rounds fired.

Results. (1) Cracking and wrinkling of the plate at the O.R. was slight but the gun steel beyond the liner was severely eroded causing a drop in accuracy after about the 300th round; (2) At the end of the test both pressure drop and velocity drop were negligible. This may be compared with a ΔV = 200 fps. after 210 rounds with P.E. bullets and unprotected gun steel; (3) It is estimated that a high velocity gun using D.B. powder should have a bore surface chromium plated for at least 32 calibers from the O.R., and preferably for the entire length.

J(F17): Chromium plate (H.C.), 0.005" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. P.E. bullets. 450 rounds fired.

During the deposition of the chromium plate the current was interrupted as a result of a blown fuse.

Results. (1) There was neither significant wear of the plate nor serious failure of the underlying gun steel; (2) Probably due to the interruption of the plating current, some layers of chromium, 0.001"-0.002" thick, were removed at various points along the liner; (3) After 450 rounds both pressure drop and velocity drop were negligible; (4) If the loss of chromium layers (2) is disregarded, there appears to be no significant difference between the erosion resistance of the L.C. plate and the standard (H.C.) plate.

J(F13): Chromium plate (H.C.), 0.005" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. P.E. bullets. 430 rounds fired.

These conditions duplicate those in J(F17) except that in this case the plating current was not interrupted.

Results. (1) The plate failed at the bullet seat and at the O.R. for 1/4"; (2) 1/2" beyond the O.R. the plate failed on the lands and the exposed steel was severely undercut; (3) Both pressure drop and velocity drop were insignificant. This may be compared with the results with P.E. bullets and unprotected gun steel after 290 rounds as follows: ΔP = -8,000 p.s.i., ΔV = -220 f.p.s.

J(F20): Chromium plate (L.C.), 0.005" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. A.T. bullets. 220 rounds fired.

Results. (1) At the O.R. the plate failed seriously, the exposed steel being severely scored and undercut; (2) The velocity drop at the end of 220 rounds was -294 f.p.s., or a ΔV -200 f.p.s. after 180 rounds. The pressure drop was -9,200 p.s.i.; (3) When A.T. bullets are used, a chromium plate 0.005" thick doubles the velocity life of the caliber .50 barrel.

J(F24): Chromium plate (H.C.), 0.005" thick on 8" steel liner. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. A.T. bullets. 226 rounds fired.

Results. (1) The plate was removed from the O.R. and from the surface of both lands and grooves for 5/8"; (2) Throughout the liner more plate was lost by the grooves than by the lands; (3) Exposed steel was severely scored and undercut causing a significant drop in pressure.

J(F27): Chromium plate (H.C.) 0.005" thick. Bureau of Standards. Electropolished. Lands 0.010" high. D.B. powder. A.T. bullets. 361 rounds fired.

Results. (1) At the O.R. plate was removed for 5/16" after 361 rounds. Beyond this the plate was cracked but still adherent; (2) Exposed gun steel was severely scored and undercut causing a large drop in pressure; (3) Since the pressure drop in caused chiefly by the erosion at the O.R., the pressure drop as a function of rounds fired indicates how soon the plate begins to fail at the O.R.

J(F34): Chromium plate (L.C.). 0.005" thick. Bureau of Standards. Electropolished. Rifled, lands 0.010" high. D.B. powder. A.T. bullets. 291 rounds fired.

Results. (1) At the O.R. the plate was removed from both lands and grooves for 1/2"; (2) Beyond the O.R. the plate, though cracked and wrinkled, still adhered to the steel; (3) Exposed gun steel was severely eroded. This caused a large drop in both pressure and velocity; (4) In J(F20) conditions were the same as in this test except that the steel surface was machined instead of being electropolished. A comparison shows that less plate was removed from the electropolished surface.

J(F40): Chromium plate (L.C.). 0.005" thick. Bureau of Standards. Rifled, lands 0.010" high. Monobloc steel barrel. Electropolished. D.B. powder. 460 grains #HES 1770.240. A.T. bullets. 311 rounds fired.

Results. (1) At the O.R. plate was removed from both lands and grooves after 90 rounds, and elsewhere there was cracking and pitting of the plate. These conditions became progressively worse; (2) A drop in velocity of 200 f.p.s. occurred after 220 rounds.

J(F41): Chromium plate (H.C.), 0.010" thick. Bureau of Standards. Monobloc steel barrel. Electropolished. Rifled, lands 0.010" high. D.B. powder. 460 grains #HES 1770.240. A.T. bullets. 83 rounds fired.

The H.C. chromium plate was deposited in 3 layers by a method which gives the overplate good adhesion.

Results. (1) At the end of the test the plate was removed in small areas up to 9" beyond the O.R. The plate which still adhered was cracked and blocks were raised above the surface; (2) Due to this roughening of the surface excessive pressure developed which caused punctured primers and extraction difficulties thus terminating the test.

J(F60): .0045" H.C. Chrome. Double Base (20% N.G.) powder.

Firing Conditions. 390 grains of Double Base (20% N.G.) powder. Pre-engraved steel banded bullets. Firing schedule III. Fired 570 rounds. Monobloc gun steel barrel 45" long. Plated on electropolished gun steel by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel showed: (1) removal of the plate from the bullet seat area started during the first erosion group; (2) as firing progressed the removal of chrome plate increased; (3) very severe erosion occurred during the third erosion group; (4) failure of the gun occurred during the fourth erosion group; and (5) velocity drop of 200 f.p.s. occurred after 490 rounds.

J(F61): .0018" H.C. Chrome plate.

Firing Conditions. 476 grains IMR powder. Pre-engraved bullets. Pressure 58,000 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds at 4 R.P.M.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) no chrome plate was removed and, (2) no checker cracking was visible.

J(F62): .0041" H.C. Chrome plate.

Firing Conditions. 476 grains IMR powder. Pre-engraved bullets. Pressure 58,600 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds at 4 R.P.M.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) no chrome plate was removed, and (2) slight checker cracking was visible.

J(F63): .0059" H.C. Chrome plate.

Firing Conditions. 476 grains of IMR powder. Pre-engraved bullets. Pressure 58,300 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) no chrome plate was removed, and (2) the checker cracking was easily visible.

J(F64): .0092" H.C. Chrome plate.

Firing Conditions. 47[illegible] grains of IMR powder. Pre-engraved bullets. Pressure 56,900 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) no chrome plate was removed, and (2) the checker cracking was easily visible.

J(F65): .0033" H.C. Chrome plate.

Firing Conditions. 398 grains of FNH-M2 powder. Pre-engraved bullets. Pressure 56,800 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) the chrome plate removed 1/8", and (2) the checker cracking very faintly visible.

J(F66): .0038" H.C. Chrome plate.

Firing Conditions. 405 grains of FNH-M2 powder. Pre-engraved bullets. Pressure 57,700 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) the chrome plate removed 3/32", and (2) the checker cracking faintly visible.

J(F67): .0055" H.C. Chrome plate.

Firing Conditions. 410 grains of FNH-M2 powder. Pre-engraved bullets. Pressure 57,000 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) no chrome plate was removed, and (2) the checker cracking was easily visible.

J(F68): .0075" H.C. Chrome plate.

Firing Conditions. 405 grains of FNH-M2 powder. Pre-engraved bullets. Pressure 56,300 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) no chrome plate was removed, and (2) the checker cracking was most pronounced.

J(F69): .0028" H.C. Chrome plate.

Firing Conditions. 365 grains of Double Base (40% N.G.) powder. Pre-engraved bullets. Pressure 55,900 p.s.i. - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) the chrome plate removed 2-1/2", and (2) the checker cracking was very faintly visible.

J(F70): .0056" H.C. Chrome plate.

Firing Conditions. 360 grains of Double Base (40% N.G.) powder. Pre-engraved bullets. Pressure 56,100 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) the chrome plate removed 2", and (2) the checker cracking was faintly visible.

J(F71): .0064" H.C. Chrome plate.

Firing Conditions. 360 grains of Double Base (40% N.G.) powder. Pre-engraved bullets. Pressure 56,900 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) the chrome plate removed 3/8", and (2) the checker cracking was easily visible.

J(F72): .0070" H.C. Chrome plate.

Firing Conditions. 363 grains of Double Base (40% N.G.) powder. Pre-engraved bullets. Pressure 58,000 p.s.i.(Cu) - Velocity 3575 to 3625 f.p.s. Fired 10 pressure rounds + 60 erosion rounds.

Liner. Plated on electropolished gun steel liner.

Results. Examination of the plated surface after 70 rounds showed: (1) the chrome plate removed 1/4", and (2) the checker cracking most pronounced.

J(F73): .003" H.C. Chrome. Double Base (40% N.G.) powder.

Firing Conditions. 355 grains Double Base (40% N.G.) powder. Pre-engraved steel banded bullets. Firing schedule II. Fired 98 rounds. Monobloc gun steel barrel, 45" long. Plated electropolished on gun steel.

Results. Examination of the fired barrel showed: (1) removal of the plate from the gun steel surface, and severe erosion of the exposed gun steel for a distance of 1.5" beyond the O.R.; and (2) a velocity drop of 200 f.p.s. occurred after 120 rounds.

J(F79): .003" H.C. Chrome. Double Base (20% N.G.) powder.

Firing Conditions. 393 grains of Double Base (20% N.G.) powder. Pre-engraved bullets. Firing schedule III. Fired 510 rounds. Monobloc gun steel barrel, 45" long. Plated on electropolished gun steel by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel showed: (1) plate was completely removed from the origin; (2) sixty per cent of the plate was removed in the section from O.R. to 4" beyond O.R.; (3) in the next 4 inches the plate was off in areas with the remaining plate cracked and wrinkled; (4) this condition of the plate diminished at 20 inches; and, (5) a velocity drop of 200 f.p.s. occurred after 470 rounds.

J(F100): .002" Chrome plate. IMR powder.

Firing Conditions. 476 grains of IMR powder. Pre-engraved bullets. Firing schedule III. Fired 820 rounds. Plated on electropolished gun steel by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel showed: (1) bullet seat and origin of rifling completely eroded away; (2) the lands were 90% eroded away from O.R. to 4" beyond O.R., and the grooves were moderately eroded; (3) the lands were 80% eroded away from 4" to 8" beyond O.R., and the grooves were scaling; and (4) from 8" beyond O.R. to the muzzle, the lands were 70% eroded away. There was scaling of the grooves.

J(71C2): .004" Chrome Plate. Double Base (40% N.G.) powder.

Firing Conditions. 360 grains Double Base (40% N.G.) powder. Pre-engraved bullets. Firing schedule III. Fired 147 rounds. Monobloc barrel plated by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel showed: (1) plating completely off bullet seat; (2) plate off land and grooves for 1-1/2" at 12 o'clock, several small areas off, deep scoring; and (3) some scoring up to 6" beyond O.R.

J(71C4): .003" Chrome Plate. IMR powder.

Firing Conditions. 478 grains of IMR powder. Pre-engraved bullets. Firing schedule III. Fired 3112 rounds. Monobloc barrel, plated by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel showed: (1) slight erosion in form of small holes appeared at the origin of rifling after

827 rounds; (2) erosion progressively increased; (3) the origin of rifling after 3112 rounds had a deep and wide groove at 12 o'clock, there was heavy pitting and spalling; (4) groove became deeper at 1/2" to 1" beyond O.R. - driving edges of the lands were badly eroded; and (5) heavy pitting and some spalling from 4" beyond O.T. to muzzle.

J(7111): .003" Chrome Plate. Double Base (40% N.G.) powder.

Firing Conditions. 380 grains of Double Base (40% N.G.) powder. Pre-engraved bullets. Firing schedule III. Fired 282 rounds. Monobloc barrel plated by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel after 282 rounds showed: (1) at bullet seat, 50% of the plating was eroded away; (2) the plating at the origin of rifling was completely eroded; (3) very deep erosion from origin to 3 inches beyond at 7 o'clock to 12 o'clock; and (4) most pronounced checker cracking throughout remainder of barrel.

J(7112): .003" Chrome Plate. Double Base (20% N.G.) powder.

Firing Conditions. 400 grains of Double Base (20% N.G.) powder. Pre-engraved bullets. Firing schedule III. Fired 825 rounds. Monobloc barrel, plated by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel showed: (1) a very deep erosion groove 1/8" from bullet seat at 3 o'clock; (2) the neck

175-13

shoulder 80% eroded away; (3) plate all off at the origin of rifling; (4) spalling in the grooves at O.R.; (5) heavy checker-work cracking from O.R. to 4" beyond; (6) lands at 6 o'clock and at 5 o'clock completely eroded for one inch in area from O.R. to 4" beyond; (7) driving edge of lands spotted with erosion; and (8) land at 5 o'clock 5 inches beyond O.R. half eroded away.

J(F113): .004" Chrome Plate. IMR powder.

Firing Conditions. 476 grains of IMR powder. Pre-engraved bullets. Firing schedule III. Fired 1232 rounds. Monobloc barrel, plated by the Philadelphia Rust Proof Company.

Results. Examination of the fired barrel showed: (1) neck shoulder and bullet seat very badly eroded; (2) several erosion grooves from origin of rifling to 3" beyond; (3) pitting and spalling in the grooves; and (4) lands eroded throughout the barrel.

L1(79): Chromium plate (L.C.), 0.005" thick. Bureau of Standards. Monobloc gun steel barrel. Length 65" (45" plus 20" muzzle extension). Electropolished. Pointed lands at the O.R. Double Base powder. P_o = 53,100 p.s.i.; V_o = 3910 f.p.s. Pre-engraved bullets. 1007 rounds fired.

The barrel was plated at the Bureau of Standards, but the muzzle extension was unplated. The plate thickness on the lands varied

176-15

from 0.0051" at the O.R. to 0.0012" at a point 32" beyond.

Results. (1) After 94 rounds, slight cracking and wrinkling of the plate was visible. After 254 rounds, blocks of plate were removed from the driving edge of the lands where they reach their full width. The pointed lands were in good condition to guide the pre-engraved bullets until after round 584; (2) The rate of erosion at the O.R. was very slow, until after round 700; (3) The combination of pre-engraved bullets with a chromium plated (0.005") bore surface showed a life 10 times that of gun steel, and 5 times that of a chromium plated barrel firing artillery type bullets under hyper-velocity conditions; (4) The radius of dispersion at 100 feet was constant to the end of the test with only one tipper.

L1(713): Chromium Plate (H.C.), 0.005" thick. Bureau of Standards. Monobloc gun steel barrel (45" length). Electropolished. Double Base powder. Lands 0.010" high. Pressure = 55,100 p.s.i., Velocity = 3860 f.p.s. Parco-Lubrized pre-engraved bullets (coating < 0.0005"). 2773 rounds fired.

The bullets were coated by the Parker Rust Proof Company of Detroit, Michigan.

Results. (1) Plate was gradually removed from the bullet seat and from the O.R. after 1711 rounds. At the end of the test, the plate had been removed from most of the bore surface to the middle of the barrel; (2) The increase in diameter of the lands was negligible to 1151 rounds, and then increased to 0.0622" at 2775 rounds. Thus the Parco-Lubrized pre-engraved bullets were very effective in prolonging the erosion life of a chromium plated (0.005") barrel; (3) The drop in pressure and in velocity was negligible to round 1581. Thereafter it increased with final values of ΔP = -15,000 p.s.i., and ΔV = -560 f.p.s.

2. COBALT AND COBALT ALLOY PLATED LINERS:

J(F35): Cobalt alloy (80% Co + 20% W) 0.006" thick. Heat treated. Bureau of Standards. Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 70 rounds fired.

After being plated the 8" steel liner was heated at 600°C, for 1 hour. This increased the hardness of the plate from 500 to 800 micro-Vickers.

Results. (1) Failure of the cobalt-tungsten plate began at the 8th round and proceeded so fast that it was not possible to establish the proper powder load; (2) Causes of failure were poor adhesion, brittleness, and melting of the plate; (3) This plate afforded no protection to the gun steel. The loss of metal was as great as that of gun steel alone.

J(F36): Cobalt plate, 0.0053" thick. Bureau of Standards. Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 153 rounds fired.

Results. (1) After 153 rounds the O.R. was still in good condition with the plate adhering to the steel surface, but beyond the O.R. the plate was pitted, scored, and cracked, probably due to both powder gas erosion and bullet wear.

J(F37): Cobalt alloy (86% Co + 14% W) 0.006" thick. Bureau of Standards. Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 156 rounds fired.

The hardness of this alloy plate was given as about 400 micro-Vickers.

Results. (1) After 140 rounds the plate was removed from the bullet seat for 1/4"; (2) The surface of both lands and grooves was badly scored and cracked showing the effects of severe gas erosion; (3) Gage measurements showed the loss of metal from the lands to be only slightly less than that of unprotected gun steel; (4) Although the alloy plate adhered to the steel, it failed to withstand the erosive effects of the powder gases under hyper-velocity conditions.

J(F38): Duplex alloy (86% Co + 14% W) 0.006" thick. Heat treated. Bureau of Standards. Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 70 rounds fired.

After being plated the liner was heated at 600°C *in vacuo* for 1 hour. This increased the hardness of the plate to more than 500 micro-Vickers.

Results. (1) At the end of the test the plate was found to be cracked and removed for small areas for the full length of the liner; (2) Gage measurements show that the erosion was severe; (3) Heat-hardening the plate increased its hardness, but also caused more cracking. It lacks resistance to powder gas erosion.

J(F39): Duplex alloy (82% Co + 18% W) 0.006" thick. Bureau of Standards. Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 150 rounds fired.

The hardness of this alloy plate was given as about 450 micro-Vickers.

Results. (1) This plate was adherent but lacked erosion resistance in a manner very similar to that of J(F37).

J(F42): Cobalt alloy (Co-W) 0.010" thick. Bureau of Standards. 8" steel liner. Electropolished. Rifled, lands 0.005" high. D.B. powder. Low pressure (52,900 p.s.i.). Ball M-2 bullets. 86 rounds fired.

The Co-W plate was deposited in two layers. The inner layer (next to the steel) contained about 10% W and was about 0.005" thick. It was plated at a current density of 2 amp/dm^2. The outer layer (bore surface) contained about 5% W and was also about 0.005" thick. It was plated at a current density of 1 amp/dm^2.

<u>Results</u>. (1) Except for a small area at the end of the liner, the plate adhered to the steel, but it was not resistant to powder gas erosion being deeply scored for the entire length; (2) Cracking was severe diminishing toward the end of the liner. Many of the cracks were circumferential indicating a lack of ductility; (3) At the O.R. the lands were swaged and eroded completely away; (4) The erosion is less than that which occurs with gun steel. The Co-W plate should be able to resist erosion caused by single base powder.

3. <u>NICKEL ALLOY PLATED LINERS</u>:

<u>J(F32)</u>: <u>Duplex plate (75% Ni + 25% W) 0.0032" thick</u>. Bureau of Standards. 8" steel liner (T-120 Ni-W#2). Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 80 rounds fired.

After deposition the plate was not heat treated. Its hardness was about 600 micro-Vickers.

<u>Results</u>. (1) Removal of the alloy plate began early and at the end of the test resulted in complete stripping of the surface for the full length of the liner. This was probably due to the lack of a good bond between alloy and steel surface; (2) The alloy plate afforded no protection to the steel which was severely eroded on both lands and grooves.

<u>J(F33)</u>: <u>Duplex plate (75% Ni + 25% W) 0.0042" thick</u>. Heat treated. Bureau of Standards. 8" steel liner (T-120 Ni-W#3). Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 70 rounds fired.

After deposition of the plate the liner was heated at 600°C for 1 hour. The hardness of the plate was 700 micro-Vickers.

<u>Results</u>. (1) The plate was removed completely for the full length of the liner, probably as a result of poor bonding; (2) Heat treatment at 600°C for 1 hour did not improve the performance of the plate.

4. DUPLEX PLATED LINERS:

J(F4): Chromium plate 0.007" thick. Over chromium a copper plate 0.0002"-0.0003" thick. Steel surface machined. Rifled, lands 0.005" high. Liner in two sections, 4-1/2" and 3-1/2" respectively. Ends plated with copper 0.005"-0.010" thick. D.B. powder. Ball M-2 bullets. 45 rounds fired.

After being plated as in J(F3) the liners were sent to M.I.T. where the copper plate was applied.

Results. (1) The copper plate soon left the chromium plated surface and produced no improvement in the erosion at the O.R.

J(F19): Chromium plate (H.C.) deposited upon copper plate. Bureau of Standards. Thickness: Cr = 0.001", Cu = 0.001". Machined surface. Lands 0.010" high. D.B. powder. A.T. Bullets. 80 rounds fired.

Results. (1) The duplex plate began to come off at the bullet seat and the O.R. after round 10; (2) The soft undercoating of copper plate is either melted or softened by the heat of the powder gases and then rubbed loose from the steel surface by the friction of the bullet; (3) The above combination of platings does not improve the resistance either to powder gas erosion or to mechanical wear.

J(F21): Chromium plate (H.C.) deposited upon nickel plate. Thickness: Cr = 0.001", Ni = 0.001". Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. 428 grains D.B. powder (HES 1770.239). P_o = 54,300 p.s.i. A.T. bullets. 80 rounds fired.

Results. (1) The soft undercoating of nickel plate failed in the same way as that of copper (J-F19). The nickel is probably softened and worn off by the friction of the bullet; (2) The above combination of plates does not improve the resistance of chromium plate either to powder gas erosion or to mechanical wear.

J(F22): Chromium plate (H.C.) deposited upon nickel plate on top of copper plate. Thickness: Cr = 0.001", Ni = 0.001", Cu = 0.001". Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. A.T. bullets. 10 rounds fired.

Results. (1) The test was terminated after 10 rounds because of the complete removal of the plate from the steel surface at the O.R.

J(F23): Chromium plate (A.C.) deposited upon a liner of chromium-copper alloy. 0.005" thick. Bureau of Standards. Machined surface. Lands 0.010" high. D.B. powder. P.E. bullets. 80 rounds fired.

An 8" liner was made from a rod of chromium-copper alloy which had been precipitation hardened by heating for three hours at 440°C. The properties of this liner are given below:

Chromium	0.85%	Harness (Rockwell B)	81
Silicon	0.10%	Tensile Strength	83,000 p.s.i.
Copper	99.95%	Yield Strength	74,500 p.s.i.

Results. (1) At the O.R. the plate was entirely removed after 80 rounds; (2) Cracking of the plate was slightly less than usual. Examination of the liner was difficult because it was destroyed in trying to remove it from the breech section.

J(F43): Duplex alloy (Co-W) plus chromium plate, 0.009" thick. Bureau of Standards. 8" steel liner. Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 83 rounds fired.

The Co-W alloy was plated in two layers. The inner layer, of about 0.005", contained about 10% W and was plated at 2 amp/dm^2. The outer layer of about 0.002", contained approximately 5% W and was plated at 1 amp/dm^2. Still another layer (bore surface) but of chromium (H.C.), of about 0.002", was deposited on top of the Co-W alloy.

Results. (1) At the O.R. checker-work cracking and loss of plate from the lands was moderate; (2) In the forward half of the liner cracking and powder gas erosion was severe; (3) Failure of the plate was due to poor adhesion at the O.R. as well as cracking and spalling along the bore; (4) The effect of the chromium plate was to protect the Co-W alloy from powder gas erosion; (5) At the end of the test the drop in pressure was negligible.

J(F44): Cobalt plate plus chromium plate, 0.010" thick. Bureau of Standards. 8" steel liner. Electropolished. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 95 rounds fired.

The thickness of the cobalt plate was 0.007" and that of the chromium plate was 0.003".

Results. (1) Throughout the liner the adherence of the plate was good except beneath the neck of the cartridge case. Difficulty with extraction terminated the test; (2) At the O.R. there was only mild cracking of the bore surface; (3) The performance of the plate was so promising it was recommended that a second liner be plated and the test repeated.

J(F91): Liner I. Cobalt-chromium duplex plate on gun steel liner. Electropolished. Bureau of Standards.

Firing Conditions. 470 grains D.B. (20% N.G.) powder. Ball M-2 bullets. Firing schedule II and III. Total rounds fired 292.

Liner. Gun steel plated with Co 0.0069" plate, followed with 0.0032" H.C. Cr plate. Bore 0.500".

Results. Examination of fired liner showed: (1) Cr plate removed from 5 lands at O.R. for 1/8". Remainder cracked and wrinkled but adhering; (2) Bore constricted in bullet seat and O.R. area. Test concluded due to pressure increase caused by constriction.

J(F92): Liner II. Cobalt-chromium duplex plate on gun steel liner. Electropolished. Bureau of Standards.

Firing Conditions. 476 grains D.B. (20% N.G.) powder. Ball M-2 bullets. Firing schedule III. Total of 501 rounds fired.

Liner. Gun steel plated with 0.0036" Co followed with 0.0025" Cr plate. Bore 0.500".

Results. Examination of liner after firing showed: (1) Plate removed from all lands from O.R. for 2"; (2) Slight pitting of surface beyond this point; (3) Severe erosion of muzzle section. Failure of liner indicated by drop in velocity mainly due to erosion of muzzle section.

J(F98): Liner III. Cobalt-tungsten chromium duplex plate on gun steel liner. Electropolished. Bureau of Standards.

Firing Conditions. 470 grains D.B. (20% N.G.) powder. Ball M-2 bullets. Total rounds fired 82.

Liner. Gun steel plated with 0.008" cobalt-tungsten alloy plate, followed with 0.0022" H.C. chromium plate. Bore 0.500".

Results. On examination after firing, these conditions were noted: (1) Cr plate completely removed from lands for 4" beyond O.R. and much from the grooves for 2".

5. MOLYBDENUM PLATED LINERS.

(a) Gun Steel Liners.

J(F25): Liner No 97G. 0.0025" thick deposited upon a steel liner. Smooth bore. D.B. powder. Ball M-2 bullets. 80 rounds fired. Firing Schedule II.

A smooth bore gun steel liner of diameter 0.515" was plated with a layer of molybdenum.

In the case of this liner the glass water saturator cracked during the plating process, as a result of which the plate was removed and the liner cleaned for the second time by electropolishing. The cleaning was not entirely satisfactory, since there were some thinly coated spots near the cartridge case neck.

Results.

(1) At the O.R. the removal of the plate, after 80 rounds, was extensive and the erosion was severe.

(2) The cause may be (a) the plate was not thick enough to prevent the formation of an altered layer of steel beneath; (b) the steel surface may not have been thoroughly cleaned, leaving small areas with an oxide coating.

J(F26): Liner No 98G. 0.0038" thick deposited upon a steel liner. Smooth bore. D.B. powder. Ball M-2 bullets. 80 rounds fired. Firing Schedule II.

The plating operation was continued for about 70 hours at a temperature of 625°C.

Results.

(1) After 80 rounds the plate was almost completely removed from the entire length of the liner.

(2) Exposed gun steel showed thermal cracking.

(3) The liner could not be forced from the breech section after firing, possibly because its physical properties had been altered during the prolonged heating at 625°C.

J(F23): Liner No 1066. 0.0032" thick deposited upon a steel liner. Smooth bore. Plating temperature 525°C. D.B. powder. Ball M-2 bullets. 70 rounds fired. Firing Schedule II.

Results.

(1) Small areas of plate were removed from the steel surface mostly toward the muzzle end of the liner.

(2) The plate showed neither thermal cracking nor other evidence of powder gas erosion.

(3) There was no permanent expansion of this liner during the test, hence it was removed from the breech section with ease.

J(F54): Liner No 312. Rifled, lands 0.005" high. Single base (IMR) powder. No erosion schedule. Ball M-2 bullets. 30 rounds fired. Plating procedure shown in Table XVIII.

Results.

(1) During rounds 16 - 20, with a charge of 450 grains, the plate began to come off in the region around the O.R., and after another 10 rounds it had been removed from all the lands.

(2) At the end of the test the plate was nearly all off the breech half of the liner and what was left on the muzzle half was blistered and nearly ready to come off.

(3) The bonding of plate to steel was weak.

J(F75): Liner No 356. Coated with .005" molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) blisters formed on the plate during the second 5-round group, and (2) the plate was removed in large areas during the 60 round erosion group.

J(F78): Liner No 360. Coated with .005" molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) plate failure in the grooves started during the first 30 rounds, and (2) after the 60-round erosion group the plate failure in the grooves increased. 90% of the plate was removed from 2 grooves in the 12 o'clock sector of the bore.

J(F80): Liner No 365. Coated with thin cobalt followed with .005" molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) the lands at the O.R. were in good condition, and (2) from the O.R. to the end of the liner small areas of Mo plate were removed from the lands and grooves.

Failure of the plate appeared to be at the cobalt-molybdenum interface, since cobalt plate was still adhering to the gun steel surface.

J(F88): Liner No 373. Coated with .0001" nickel and then .005" molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 30 rounds.

Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) failure of the Mo plate on bullet seat started at 49,000 p.s.i. pressure, (2) continued firing caused stripping of plate from bullet seat, lands and grooves for a distance of 1-1/4" beyond the O.R., and (3) from 1-1/4" to the end of the liner the plate was in good condition.

J(F89): Liner No 374. Coated with .0005" cobalt and then .005" molybdenum.

Firing Conditions. Gradually increased load of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) small areas of Mo plate were removed from the bullet seat and grooves at the origin of rifling, (2) the lands from O.R. to 4" beyond O.R. were in good condition, and (3) 50% of the plate was removed from the land and groove surface at 4" to 8" beyond O.R.

J(F90): Liner No 375. Coated with .0005" cobalt and then .001" molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) slight Mo plate removal from the edge of the bullet seat occurred after 30 rounds, and (2) after 100 rounds areas of plate were off the bullet seat, all lands at the O.R. and from the land and groove surface throughout the liner.

J(F92); Liner No 376. Coated with .0005" nickel followed with .005 molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds. Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) removal of Mo plate from bullet seat and grooves for 1-1/2" beyond O.R. occurred after the first 30 rounds, and (2) after 100 rounds 50% of the plate was removed from the bullet seat and O.R. area.

J(F97); Liner No 380. Coated with .0001" platinum, then .0001" cobalt and then .005" molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 30 rounds. Plating technique shown in Table XVIII.

Results. Examination of the fired liner showed (1) 50% of the Mo plate was removed from bullet seat and O.R. area after 30 rounds.

J(F105); Liner No 395. Coated with .010" molybdenum.

Firing Conditions. Gradually increased loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds. Plating technique shown in Table. XVIII.

Results. Examination of the fired liner showed (1) no plate was removed from the edge of the bullet seat after 30 rounds, (2) after

100 rounds plate was removed completely from the bullet seat, (3) 90% of the plate was removed from land and groove surface at O.R. and to 4" beyond O.R., and (4) from 4" to 8" beyond O.R. 50% of the plate was removed from the land groove surface.

(b) Mo plated Stellite #21 Liners.

J(F43): Liner No 271GS. Coated with molybdenum 0.003" thick. Rifled, lands 0.005" high. D.B. powder. Ball M-2 bullets. 87 rounds fired. Firing Schedule II.

The molybdenum plate was deposited upon the stellite surface from molybdenum carbonyl vapor. The liner was first heated and plated with a very thin protective coating at 625°C, then heated to 900°C and cooled immediately to the plating temperature. This required about 10 minutes. The liner was then plated at 590°C for 33 hours. The resulting plate had a hardness of about 600 micro-Vickers.

Results.

(1) Removal of molybdenum began on the 4th round at reduced pressure and at the end of the test was nearly complete for the full length of the liner.

(2) The failure of the plate occurred in the following sequence: (a) appearance of a small circular dark area, (b) which becomes a blister, (c) then spalling of the plate.

(3) The exposed stellite showed a network of cracks which were very severe at the breech end of the liner.

(4) The liner failed because of poor adhesion of the molybdenum plate to the stellite surface which, of itself, is not resistant to the attack of the gases from double base powder.

J(F49): Liner No 285. Coated with molybdenum 0.0015" thick. Rifled, lands 0.005" high. D.B. powder. All rounds at reduced charge. Ball M-2 bullets. 6 rounds fired.

Results.

(1) At the O.R. removal of the plate began at the 2nd round and extended rapidly the full length of the liner. Failure was evidently caused by poor adherence of the plate to the liner.

J(F50): Liner Mo 290. Coated with molybdenum 0.0015" thick. Rifled, lands 0.005" high. Single base IMR powder. Ball M-2 bullets. 14 rounds fired.

The fabrication of the liner and its coating was the same as that described in J(F49).

The flame temperature of this IMR powder was about 600°C lower than that of the double base powder ordinarily used.

Results.

(1) Removal of plate from the stellite surface began after the 3rd round and grew worse but it was not as severe as with double base powder.

(2) Poor adherence of the plate to the bore surface may be due to selective diffusion of the molybdenum into the stellite, the failures occurring where little or no molybdenum has diffused below the stellite surface.

J(F51): Liner Mo 292. Coated with molybdenum 0.003" thick. Rifled, lands 0.005" high. Single base IMR powder. Ball M-2 bullets. 86 rounds fired. Firing Schedule II.

Results.

(1) The plate blistered after the 12th round, and by the end of the test this condition had spread throughout the liner resulting in the loss of molybdenum from many small areas.

(2) Under similar conditions ΔL, ΔV and ΔP were all less than when double base powder was used.

J(F52): Liner No 295. Coated with molybdenum 0.003" thick. Rifled, lands 0.005" high. Single base IMR powder. Ball M-2 bullets. 14 rounds fired.

This liner was plated twice because of trouble in plating operation.

The second plating was substantially the same as that described in J(F49). The total plating time was 31 hours.

Results. (1) The plate began to fail at the third round, the nature of the failure being the same as that already described above.

J(F53): Liner No 307. Coated with molybdenum 0.003" thick. Rifling, lands 0.005" high. Single base IMR powder. Ball M-2 bullets. 40 rounds fired. Firing schedule V.

After etching oversize, the liner was heated in vacuo at 1000°C for 11 minutes and cooled. After a slight additional etch to clean the surface, the liner was plated for 24.5 hours at a carbonyl temperature of 29°C and a hydrogen pressure of 0.075 mm. In other particulars, the treatment was identical with that given the liner in J(F49).

Results. (1) The plate failed before the 10th round with a charge of 350 grains and a pressure of only 51,500 p.s.i. The failure grew worse as firing progressed.

1151

J(F55): Liner No 315. Coated with molybdenum 0.005" thick. Rifled, lands 0.005" high. Single base IMR powder. Ball M-2 bullets. 90 rounds fired. Firing Schedule V.

Plating procedure shown in Table XX.

Results.

(1) After 20 rounds the molybdenum plate appeared to be unchanged, but failure occurred during the next 60 rounds.

(2) Plate was removed from the lands only at the O.R. and 3/4" beyond. Plate in the grooves was not damaged.

(3) Failure of the plate occurred where engraving stresses were highest, hence it may be due to (a) thinning of the molybdenum plate and/or (b) inability of molybdenum plate to withstand the engraving stresses or the wear caused by friction of the bullet.

J(F57): Liner No 338. Coated with molybdenum .0047" thick.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 230 rounds.

Plating procedure shown in Table XX.

Results. Examination of the fired liner showed (1) plate was unchanged after the usual 30 pressure rounds, (2) after first erosion group there was slight failure on the driving edge of the land just beyond the O.R., (3) the plate was removed from the lands for a distance of 1-7/8 inches beyond O.R. after the second erosion group and (4) there was no plate failure in the grooves.

Test was concluded because of land failure.

J(F58): Liner No 343. Coated with .005" molybdenum.

Firing Conditions. Gradually increased loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating procedure shown in Table XX.

Results. Examination of the fired liner showed (1) failure of the plate started on the driving edge of the lands, (2) serious removal of the plate from the lands and grooves for the entire length of liner after the first erosion group, and (3) groove failure probably partly caused by gas leakage.

Test was concluded because of both land and groove failure.

J(F59): Liner No 349. Coated with .005" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating procedure shown in Table XX.

Results. Examination ofthe fired liner showed (1) plate was adhering to Stellite surface after 240 rounds, and (3) no breaking along the driving edge of the lands.

J(F74): Liner No 353. Coated with .003" molybdenum.

Firing Conditions. Gradually increasing loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) plate started failing during the first 5 rounds and (2) pressure drop of 13,300 p.s.i. after 100 rounds.

Test was concluded because of this plate failure.

J(F76): Liner No 357. Coated with .005" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) plate was removed from the driving and leeward edges of the lands for 2-1/2 inches and (2) no removal of plate from grooves.

Test was concluded because of the land failure.

J(F77): Liner No 362. Coated with .005" molybdenum

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) failure of the bond started during the third 5-round pressure group, (2) after 30 rounds the plate failure extended to 2-1/2 inches beyond the O.R., and (3) large areas of plate were removed from the land and groove surface after 100 rounds. For this reason the test was concluded.

J(F81): Liner No 366. Coated with .005" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 100 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) plate failure on the lands started during the 15 pressure rounds at 58,300 p.s.i.(cu.), (2) plate failure occurred on the lands for a distance of 3/8" beyond the O.R. after 100 rounds, and (3) no plate failure in the grooves.

Test was concluded because of the above land failure.

J(F32): Liner No 367. Coated with .005" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) plate failure on the driving edge of the lands started during the 15 pressure rounds at 57,600 p.s.i.(cu.), (2) after 100 rounds the condition of the plate was the same as in Liner No 366 (J(F31)), and (3) after 240 rounds 40% of the plate was off the bullet seat, completely off 8 lands at the O.R., and for a distance of 3/4" beyond O.R. and in small areas off the grooves. Beyond the O.R. the driving edge of the land was chipped. Test was concluded because of this condition.

J(F33): Liner No 368. Coated with .007" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) after 100 rounds the only failure was chipping along the driving edge of the lands for 1/10" at the O.R., (2) after 240 rounds, the plate was off the edge of the bullet seat and the driving edge of all lands at the O.R. and (3) beyond the O.R. the land and groove surface was unchanged.

J(F35): Liner No 369. Coated with .005" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullet. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) after 100 rounds the plate was off the edge of bullet seat, chipped on driving edge of all lands at O.R. and up to 4" beyond O.R., (2) after 240 rounds 50% of the plate was off the bullet seat in the 12 o'clock sector - partially off the lands at the O.R. and off in small areas in the grooves up to 1-1/2" beyond the O.R., and (3) beyond 1-1/2" the plate was in good condition, except for slight chipping on driving edge of lands.

J(F36): Liner No 372. Coated with .007" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) no failure of the plate was observed during the first 100 rounds, (2) after 240 rounds, slight failure occurred on the driving edge of the lands and in the grooves, and (3) beyond 1/4" from the O.R. the plate was in good condition.

J(F94): Liner No 378. Coated with .007" molybdenum.

Firing Conditions. Gradually increasing loads of single base IMR powder. Ball M-2 bullets. Firing Schedule V. Fired 30 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) plate failure occurred in the first five pressure rounds, (2) continued firing caused more removal of plate from the lands, and (3) plate failure occurred on the lands at 3 and 5 o'clock for a distance of 1-1/2 to 2-1/2 inches.

J(F95): Liner No 379. Coated with .0075" molybdenum.

Firing Conditions. Gradually increasing loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) small holes were made by tearing away of the nodules after 30 pressure rounds, (2) after 100 rounds failure progressed at the small holes and (3) severe plate failure erosion of the exposed stellite occurred after 240 rounds.

J(F103): Liner Mo 393. Coated with .008" molybdenum.

Firing Conditions. Gradually increasing loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table XX.

Results. Examination of the fired liner showed (1) no failure at O.R. after 30 rounds, and (2) plate was removed from bullet seat and grooves after 100 rounds. The exposed stellite was severely eroded after 240 rounds.

J(F107), J)F108), J)F109): Liners Mo 297, Mo 399, Mo 404. Coated with .010" molybdenum.

Firing Conditions. Gradually increasing loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule V. Liner Mo 397 was fired 240 rounds; the other liners (Mo 399 and Mo 404) were fired 100 rounds.

Plating technique shown in Table.XX.

Results. The liners failed in the same manner. Examination of the fired liners showed (1) liners Mo 399 and Mo 404 showed slight peeling of plate after 30 rounds and severe failure after 100 rounds, and (2) liner Mo 397 showed slight peeling of plate after 100 rounds and severe failure after 240 rounds.

701-12

J(F110): Liner No 405. Coated with .0125" molybdenum.

Firing Conditions. Gradually increasing loads of double base (20% N.G.) powder. Ball M-2 bullets. Firing Schedule V. Fired 240 rounds.

Plating technique shown in Table IX.

Results. Examination of the fired liner showed (1) slight failure of the plate along the edge of the bullet seat after 30 rounds, (2) after 100 rounds small areas of plate were removed from the grooves near O.R., and (3) after 240 rounds, there was severe scoring of the exposed Stellite surface.

208-13

6. SPRAYED MOLYBDENUM COATINGS:

J(F29): Molybdenum plate "sprayed and roller welded". Massachusetts Institute of Technology. 8" liner coated with Mo for 2". Smooth bore. D.B. powder. Ball M-2 bullets. 51 rounds fired.

The method of fabricating this liner was devised by Prof. John Wulff. A carbon mandrel was first coated to a thickness of 0.020"-0.050" with molybdenum by means of the spraying technique. The coated mandrel was then sintered in hydrogen to reduce the oxide content and to promote densification. After sintering, the mandrel, together with its coating, was ground to a 1/32" per foot taper for 2" of its length. The smooth bore gun steel tube was then ground to the same taper and plated with 0.001" of copper. The mandrel was cooled in liquid air and pressed into the gun tube by a force of 300 lbs. The carbon mandrel was finally bored out and the interior surface was ground to a diameter of 0.510".

Results. (1) The molybdenum surface developed a deep crack during the first 16 rounds, but there was no change in its appearance after 51 rounds. The cause of the crack was probably a lack of ductility in the molybdenum and a failure to follow the expansion of the steel liner during firing; (2) There was no checker-work cracking; (3) There was an increase in diameter of the smooth bore of 0.002" due to permanent expansion of the liner.

J(F30): Molybdenum plate containing 1/2% nickel. Spraying and roller welding technique. Massachusetts Institute of Technology. 8" steel liner, coated with Mo + 1/2% Ni for 2". Smooth bore. D.B. powder. Ball M-2 bullets. 45 rounds fired.

263??

The technique of fabricating this liner was the same as that described in J(F29). The purpose of spraying nickel with the molybdenum is to produce a density of the sprayed coating of over 99% after sintering in hydrogen.

Results. (1) At the end of 10 rounds the coating had 3 longitudinal cracks at the breech end of the liner. After 45 rounds there were 7 such cracks, 3 of which were at the muzzle end of the coating. The cause of the cracking was the same as in J(F29); (2) There was no checker-work; (3) There was an increase in diameter of the smooth bore of 0.0025" due to permanent expansion.

J(F31): Molybdenum plate containing 1/2% nickel and 3% copper. Spraying and roller welding technique. Massachusetts Institute of Technology. 8" steel liner coated for a length of 2". Smooth bore. D.B. powder. Ball M-2 bullets. 45 rounds fired.

The technique of fabricating this liner was the same as that described in J(F29).

Results. (1) The only difference between the erosion observed and that described in J(F30) and J(F29) is that more cracks developed and the surface was pitted.

7. PARCO LUBRITE COATINGS:

J(F45): Parco Lubrite coating on monobloc gun steel barrel. Coating 0.0005" thick. Rifled, lands 0.010" high. .B. powder. A.T. Copper banded bullets. 159 rounds fired.

The Parco Lubrite coating produces a chemical reaction on the bore surface which results in a non-metallic oil-absorptive film consisting chiefly of a mixture of iron and manganese phosphates. The gun bore was given this treatment by the Parker Rust Proof Company, Detroit, Michigan.

Results. (1) There was severe cracking and incipient melting of the bore surface at and beyond the O.R.; (2) A comparison of the erosion characteristics of this test with those in the control tests C(F6) and C(F12) shows that the Parco Lubrite bore does not improve the performance of the barrel even in a single particular.

205-13

16 November 1945

PREVIOUS

TEXT:

GROSS R.

Comments by J. F. Schairer on "Final Report from the Franklin Institute entitled, "The Behavior of Gun Liners and Coatings Tested under Conditions of Hypervelocity"

page 1

Chromium plate is not listed as one of coatings tested

The Harvard Report lists Cu plate--this is not covered at all in the FI report

last line - Change "as the outer coating" to "as the bore surface material"

page 2

Under section 1 line 2 add "breech" after the word "short"

line 3 add "bore surface" before "coating"

page 5

Why not state in what direction "copper" pressures differ from true piezoelectric measurements of pressure

page 6

line 2 - insert the word "breech" before "liner"

The sentence forming lines 6 and 7 is ambiguous (the phys. properties were not "thus tested in the form of liners")

Table II, p. 7

Table II is unsatisfactory as follows: No data on elongation or reduction of area are given. These have an important bearing on behavior ~~in~~ of the liner. The data quoted under SAE 4150 is that for WD 4150. In Table II since no compn.

706-11

Table II (comments continued)

is given for silicon steel properties mean nothing. The mp of Cr is taken from Internat. Critical Tables and does not represent the better data obtained by Climax and Westinghouse. Data for cobalt is for cast metal which values have little bearing on properties of plated metal - same applies to copper

Mo tensile strength 256 - 315 x 10^3 psi should be explained - only on fine wire and not on material of suitable size for a liner. Also hardness varies with amt. of mechanical working.

W - 577.4 x 10^3 psi for tensile strength should be explained -only on fine wire.

Some data on tensile strengths of Cr-base alloys are available in Climax reports.

Table III, p. 8

line 2 - "SAE 4150" should read "WD 4150"

Why is SAE 9260 included in this table?

Is nothing more available on the silicon steel than that it had 4.7% Si?

Under stellite No. 21 ranges of compn. are given except for Mo and there is no mention of Ni (which is always present) and iron is more than a small amount - why not use the Army specifications for stellite No. 21 compn.?

Why is stellite No. 6 listed here? It was not tested at FI.

page 13 section 1 (a) line 1

"better" ~~thn~~ than what?

section 1 (a) line 4

Change to "manufacture from metal powder by powder metallurgy"

701-13

page 13 (continued)

section 1 (a) line 6

Change "proper work and heat treatment" to "intensive mechanical working accompanied by suitable annealing treatments"

section 1 (a) lines 7 & 8

Change to "Powder metallurgy ingots intensively worked in only one direction give etc"

section 1 (a)

At end of first paragraph add the sentence:- "Mechanical working (cold work) increases the strength, hardness and ductility of molybdenum"

section 1 (a), second paragraph,

Change first sentence to "Many of the early liners tested had no mechanical working or insufficient mechanical working and consequently they failed after a few rounds by longitudinal cracking or by surface cracking and spalling of metal."

p. 13 near bottom under <u>Low Hot Hardness</u>

Change first sentence to:- "Pure unworked molybdenum or pure molybdenum which had had insufficient cold working has been shown to be too soft at the temperature reached in guns during firing to withstand the engraving stresses. As a result there is a gradual deformation of the rifling (particularly at or near the origin of rifling) by the swaging impact of jacketed ot banded projectiles."

205-15

page 14

line 1 - after "hardened" add "either by intensive cold working or by a combination of alloying and cold working,"

lines 3 & 4 - after "material" say "shows excellent resistance to powder gas erosion"

under "Low Coef. of Expansion" line 4 - change "out of line" to "out of alignment"

and line 5, at end of this line add "from rotation"

page 14

under "Low Coef. of Expansion" near bottom of page change line 1 "corrected" to "counteracted"

page 17

Comment on item(3) Barrel Temperature Measurements

This item is of general interest not only for Mo liners but also all liners tested and should be moved to section A(3) "Conditions of Firing" which begins on p. 3 of this report

page 22

under (h) Composition - Change first sentence to "The pure molybdenum so far tested was too soft to withstand engraving stresses without some deformation of the rifling." and add "It may be possible to correct this by a change in the fabrication process to start with larger metal ingots which will permit more hardening by intensive cold working."

and in line 4 delete "(hot working)" - in the case of molybdenum most of the forging takes place below the recrystallization temperature and although "hot" is really cold working.

209-15

page 22 Under (h) Composition in line 4

After the word "comparison" put an asterisk and the following footnote:

"Attention should be called, however, to the fact that these liner materials were produced while developing a fabrication schedule and the several materials were not all subjected to the same amount of cold working or comparable working and annealing schedules."

page 22 Last sentence - Change to "These results suggest that Mo with 0.1% Co gives the best and most consistent performance."

page 30

First line - insert the word "cast" before "chrome base alloy liners."

page 31

Line 8 - change (d) to: "Dimensional changes due to improper stress relief of one of the liner castings caused a bore constriction thereby resulting in excessive powder pressure"

page 35 - top of page

Add a section (e) Tantalum is available only in thin walled seamless tubes. If tantalum liners were used it would be necessary to find a satisfactory method of attachment in the gun bore. In order to perform the firing tests described the thin walled tubes were inserted in a steel shell and the tantalum held in place by a deliberate galling of tantalum against steel.

310-15

page 36

line 1 - after "boredrilled" add "from cast tubes"

line 4 - Change "Stellite is" to "Stellites are"

line 5 - Change "It is" to "They are"

line 7 - Change "alloy" to "alloys" and "is" to "are"

line 8 - Change "it has a melting point" to "Stellites have melting points" and lines 8 and 9 "being" to "and lie in the range between 1250 and 1320°C"

page 40

last line of (2) z-nickel - change to "is characteristic of most high-nickel alloys"

page 46

2nd last paragraph on this page -

I would not use the words "adheres well." In the process just described, there is no question of lack of adhesion (inadequacy of the chromium to steel bond) but failure is by undercutting. I would say "there is no undercutting and the chromium remains on the steel bore surface."

page 46 2nd last line -

Change "adhering" to "remaining" or delete "adhering"

page 57

Under Conclusions

(a) Change to "Chrome plate is resistant to powder gas erosion (both chemical attack and melting)."

page 60

Change first sentence to "All the liners tested failed by melting of the surfacd."

511-13

CONFIDENTIAL

page 62

Under (a) Composition

Change 2nd line "Severe gas erosion" to "Melting"

Just below middle of page - delete "gas erosion" and take "(melting)" out of parentheses

page 63

Under (1) Types of Failures Observed -

This report lists only low melting point. The Harvard Report also cites lack of chemical resistance.

Under Low Melting Point -

Change to "All liners failed by a combination of chemical attack and melting."

~~and~~ on p. 148 of the F.I. report the cause of failure is stated as poor bonding. There is no mention of poor bonding in the Harvard Report.

page 65

Under item (1)

Change last sentence to "Practically 100% of the plate was removed from the bore surface principally by melting but the removal may have been accelerated by simultaneous chemical attack presumably by sulfur from the powder gases."

Under (3) Conclusions

Change to "Nickel-tungsten alloy plates do not have the proper combination of thermal properties and resistance to chemical attack by powder gases for bore protection under hypervelocity conditions."

page 66

Under (a) Erosion Resistant Properties of the Duplex Plates Tested

The first sentence is not quite a true statement. When .007" Co + .003" Cr was one of the duplex plates tested one can hardly say "All the duplex plates tested have used chromium as the main plate to protect the gun steel against the thermal effects of powder gases."

After the end of the first paragraph under this section I would add something like this - "Undercoats beneath chromium plate were tried to improve the performance of chromium by preventing the "mushrooming" of cracks in steel beneath chromium as described on page 46 of this report. Erosion resistant metals (or materials thought at the time of test to be erosion resistant--viz. nickel) were used as undercoats even though their melting points were known to be relatively low."

Then add a paragraph -

"In the case of a thick undercoat (0.007") of cobalt under 0.003" of chromium, the duplex plate prevents thermal alteration of steel. Ductile and chemically resistant cobalt is protected from melting by the chromium. When the chromium plate cracks, powder gases entering cracks reach chemically resistant cobalt instead of easily attacked and altered steel. The cracks do not "mushroom." "

page 67

Items (f) and (g) near top of page

The purposes alleged for these tests are at variance with allegations in previous sections of the F.I. report, where it was

213-15

page 67 (continued)

pointed out that adherence of Cr plate was not a problem and that undercutting and chemical attack of steel beneath the plate caused failure. The purpose of tests of (f) and (g) should have been to provide

(1) an erosion resistant base (and in the case of the Co-W alloy a base that was both erosion resistant and hard enough to prevent deformation during firing) which would improve the utilization of Cr with its high melting point but unfortunate tendency to crack.

page 71 first line

What is meant by "severe gas erosion" - melting? or chemical attack? or both?

page 97

Under E(F5) and E(F6) - Liner made by boring a 3/4" swaged rod

Under E(F7) - Liner B-16-4 was bored from a rod of unworked molybdenum

and E(F10) - Liner made by boring a 3/4" swaged rod

page 99

Under E(F11) - Liner made by boring a 3/4" swaged rod

page 118

Under E(F29)

Line 7 and line 9 - Change "due to volume change in the Cr-base alloy" to "due to dimensional changes in the bore probably caused by failure to relieve casting stresses"

(No volume changes have been observed in Cr-base alloys.)

3/1/-13

page 113 (contd)

Under E(F30) <u>Results</u> section item (2)

Change to "Constriction of grooves due to dimensional changes"

page 145

Under J(F36) <u>Results</u> section

Explain "powder gas erosion" by parenthetical "(melting)".

Under J(F37) <u>Results</u> section item (2)

Explain "severe gas erosion" by parenthetical "(melting)".

page 146

Last sentence under J(F38) - What is meant by "powder gas erosion"? melting? or chemical attack? or both?

page 148

In both tests J(F32) and J(F33) the statement is made that failure was due "to the lack of a good bond between the alloy and steel surface" or "plate was removed probably as a result of poor bonding"

This does not check with "types of failure observed described" on page 63 of this F.I. Report or with Harvard's findings.

page 149

Under J(F19) last few words

What is meant by "powder gas erosion"? chemistry? or melting? or both?

pages 149 & 150

Last few words on p. 149 and first few on p. 150 - This does not check with the statement made on p. 70 of this report where pages 149 & 150 (contd)

both softening and cracking around crystal grains admitting gases to the underlying steel were given as reasons for failure.

page 150

line 2 - Explain "powder gas erosion" - chemistry? or melting? or both?

page 151

lines 6 and 9 - Explain "powder gas erosion"

page 154

middle of page - Explain "powder gas erosion"

page 159

near bottom of page - 4th & 5th last lines - Has it been shown that stellite No. 21 "is not resistant to the attack of the gases from double base powder"? Is not the effect of such gases merely a thermal one (melting)?

page 167

lines 4 and 5 - There is a word missing, probably "and"

216-13

FILE:
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IRVIN STEWART, Executive Secretary

Address Reply to
Division One, NDRC
2101 Upton Street, N. W.
Washington 25, D. C.

29 October 1945

Dr. H. B. Allen, Deputy Chief
Division One, NDRC
The Franklin Institute
Parkway at 20th Street
Philadelphia 3, Pennsylvania

Dear Dr. Allen:

Franklin Institute Report on Gun Liners etc.

Herewith I am returning copy No. 2 of the report by the Franklin Institute under contract OEMsr-533, entitled "Final Report on the Behavior of Gun and Coatings under Conditions of Hyper Velocity". This is an excellent contribution and I am delighted that it has been prepared. The following are a few comments which I offer for consideration in connection with its final review by your office.

On Figure 25, which follows after page 58, the O.R. at the end of the second line of the legend is likely to be confusing to some readers — as it was to me on first looking at it. I missed the periods and, until I came back to it a second time, read this as "or". If it is not convenient to expand the abbreviation on the diagram, perhaps the periods could be made a little heavier before final reproduction.

Page 10, line 8 from bottom. The word "melting" is given in quotation marks, presumably to leave it an open question as to whether erosion in a gun is characterized by a melting of the bore surface. This appears to cast unnecessary doubt on the reality of melting, which, as a result of some of the investigations under Division One, seems to have been thoroughly established.

Page 13, line 2 from bottom. It probably would be desirable, for easy reading, to add the word "pure" before the word "molybdenum".

Page 24a, section 6c. ". . . the following composition and design

FOR VICTORY BUY UNITED STATES WAR BONDS AND STAMPS

characteristics have given the best results ..." The list includes the two-stave construction; but on page 21 it is admitted that the twisted two-stave liner remained in better condition than a straight two-stave liner. Perhaps a further explanation is needed as to what is meant by "best results".

Page 72, section 5. A further word or two in explanation of the difference in process of applying the molybdenum plate, in comparison with the previous electroplates might be desirable.

There is another matter of verbiage in this and other reports that I would like to call attention to, although it may not be practicable at this stage to do anything about it. I refer to the use of the word "chrome" in place of "chromium" whenever it precedes "plate" or"plating". Apparently, chrome is an allowable synonym, but I see no point in using it except to save a trifling amount of space. The word chrome is more general in meaning, and in some cases, therefore, less informative. Thus, we have chrome-tanning as a process using chromium salts and we have chrome-brick for articles containing some chromite. If we mean chromium to describe a certain composition of plate, why do we not use that word? This is probably relatively unimportant but I thought I would raise the question.

Very truly yours,

L. H. Adams

L. H. Adams
Chief, Division One

encl

213-15

Letter of Submittal

Division One
National Defense Research Committee
of the
Office of Scientific Research and Development
Washington, D. C.

28 June 1946

My dear Mr. Norcross:

I have the honor to forward herewith a report entitled "The Behavior of Gun Linersand Coatings Tested Under Conditions of Hypervelocity", which had been submitted to Division One by Dr. Nichol H. Smith, Technical Representative for Contract OEMsr-533, with a letter of transmittal dated 16 October 1945. It is to be considered the final report of this specific project under contract and covers the work performed from 1 August 1942 to 28 February 1946.

The work described in this report is pertinent to the project designated by the War Department as OD-52 entitled "Gun Erosion, Including Hypervelocity Gun Studies," and to the project designated by the Navy Department as NO-23 entitled "Gun Erosion." During its later stages it was carried out under the guidance of the Erosion Project-Control Committee.

I have accepted this report and have approved it for duplication and issuance as a formal report from Division One to the National Defense Research Committee. The initial distribution of the report appears on the following page.

Respectfully submitted,

L. H. Adams
Chief, Division One

Mr. Cleveland Norcross, Executive Secretary
National Defense Research Committee

219-B

219-B

FOREWORD

Erosion-Resistant Materials Program of Division 1, NDRC

In an early stage of the studies of gun erosion by Division 1, NDRC, the conclusion was reached that, because of their lack of resistance to thermal and chemical attack by powder gases during firing, no steels or high-iron alloys showed promise as bore-surface materials under severe firing conditions using conventional propellants. Yet steels are the only materials of adequate strength and ductility that are available in sufficient quantities for gun tubes. Therefore, in order to protect the bore surface of such steel tubes from contact with powder gases (at least near the breech end where powder-gas erosion is most severe), attention was concentrated on the development of suitable erosion-resistant liners, linings, electroplates, and other coatings.

Laboratory tests showed that only the following pure metals were resistant to chemical attack by the powder gases: chromium, molybdenum, tungsten, tantalum, nickel, cobalt, and copper. Only the first four of these have a sufficiently high melting point for severe service under hypervelocity conditions, where melting is an important factor in the failure of a steel gun-bore surface. Other tests showed that in addition to suitable resistance to thermal and chemical attack, a bore-surface material must have sufficient hardness and strength at temperatures attained during firing to prevent deformation of the rifling by impact of the projectile and must be sufficiently ductile to prevent serious failure by cracking.

In the fall of 1942 efforts were started on the preparation of chromium and molybdenum in form suitable for use as gun liners. By the following summer preliminary tests of molybdenum liners had emphasized the importance of hot-hardness as a characteristic of a successful gun-liner material. Further study of this phase of the subject led to the discovery that the stellites, which are cobalt-chromium alloys that have the property of hot-hardness, are erosion-resistant as long as the bore-surface temperature is not too high. By that time the experience of aerial combat during World War II had indicated that erosion was limiting the performance of the caliber .50 aircraft machine gun. Application of the discovery of the erosion-resistance of stellites to this problem led to a remarkable increase in the performance level of this gun. A parallel attack on this same problem led to the development of nitrided, chromium-plated caliber .50 barrels. Eventually it was found that an even better barrel was obtained by using a stellite liner with the steel bore chromium-plated ahead of it, provided that the steel barrel was strengthened by making it slightly heavier (especially at the forward end of the liner) and perhaps by using a special steel having greater strength at high temperature.

Experience with stellite liners in the caliber .60 machine gun, which has a muzzle velocity of slightly over 3500 ft/sec, showed that this alloy is "marginal" with respect to its use in a hypervelocity gun. In this particular application a stellite liner lasts long enough to furnish a useful gun-barrel life, but when it fails, it does so by melting along surface cracks. That fact coupled with the observation that the surface of a stellite liner melts when fired with double-base powder, even at velocities around 3000 ft/sec, showed that a material of higher melting point was needed for general use in hypervelocity guns, that is, ones firing at muzzle velocities greater than 3500 ft/sec. Hence the search for such a material was continued at the same time that further efforts were made to extend the application of stellite.

Some phases of both groups of investigation were carried out by the same contractors of Division 1, among whom a remarkable spirit of cooperation was evident. This cooperation was fostered by the formation in October 1944 of the Resistant-Materials Project-Control Committee, to the monthly meeting of which the different contractors sent representatives. It was only through their continual willingness to help each other that so much was accomplished in such a short time.

During World War II caliber .50 gun barrels that had been nitrided and chromium-plated and others that had had stellite liners inserted in them were used in combat. Production of stellite-lined barrels of other sizes was ready to start at the time of

19-206

Japanese surrender. The further application of stellite and other hot-hard alloys to small-arms barrels is being continued by the Crane Company for the War Department. Continuation of the investigation of chromium electroplates, of duplex electroplates of chromium and other metals, and of alloy electroplates of various pairs of metals at the National Bureau of Standards is being supported jointly by the War and Navy Departments.

The most promising material for general hypervelocity service appears to be a hardened molybdenum. Sufficient progress was made in its development during World War II so that now the Navy Department is supporting the efforts of the Westinghouse Electric Corporation to make this material in a form suitable for gun liners, following the plans developed under the auspices of Division 1, NDRC. Similarly, the War Department plans to have the Union Carbide and Carbon Research Laboratories continue the development of chromium-base alloys, which also appear very promising for hypervelocity service. Vapor-phase plating does not appear to be suitable for gun bores, and therefore it is not being continued for this purpose, although it may have industrial applications.

Thus the resistant-materials program of Division 1, NDRC, during the past three and a half years has led to the development of a very successful solution to the erosion problem in machine guns and narrowed the search for bore-surface materials capable of outstanding performance under hypervelocity conditions to three clearly defined programs, all of which are now being pursued by the Armed Services. The work carried out by the contractors of Division 1, NDRC, in the development of erosion-resistant materials is described in a series of 28 reports. They are listed on the following pages for convenience in reference and also as an indication of the scope of the resistant-materials program. To them have been added the titles of five other reports dealing with stellite liners and chromium-plated gun bores, which were prepared under the supervision of the Liners and Coatings Project-Control Committee.

December 11, 1945

J. S. Burlew, Chairman

J. F. Schairer, Secretary

Resistant-Materials Project-Control Committee
Division 1, NDRC

REPORTS ISSUED BY DIVISION 1, NDRC, DEALING WITH EROSION-RESISTANT MATERIALS

Report Number NDRC	OSRD	Title, Author, Contractor
		A. General Materials Testing and Liner Development
A-148	1249	"Metals tested as erosion vent plugs," by O. H. Loeffler, G. Phair, and H. S. Jorabek. Geophysical Laboratory, C.I.W., Contract OEMsr-51
A-403	6474	"The results of erosion vent-plug tests particularly under conditions of decreased severity and their application to the erosion of guns," by H. S. Jorabek, G. Phair, D. Enagonio, and C. A. MacQuaid. Geophysical Laboratory, C.I.W., Contract OEMsr-51
A-404	6475	"The behavior of gun liners and coatings tested under conditions of hypervelocity," by N. H. Smith. Franklin Institute, Contract OEMsr-533
A-405	6476	"Metallographic examination of gun liners and coatings tested under conditions of hypervelocity," by J. N. Hobstetter. Harvard University, Contract OEMsr-537
A-406	6477	"Erosion tests of materials in the form of short liners in a caliber .30 machine-gun barrel" by J. Wulff. Johnson Automatics, Inc., Contract OEMsr-465
A-407	6478	"Search for erosion-resistant materials for guns by firing particles of metal and alloys into a vacuum to determine their structural and chemical behavior," by E. Posnjak. Geophysical Laboratory, C.I.W., Contract OEMsr-51
[illegible]	[illegible]	[illegible]
A-408	6479	"Gun-barrel liners — materials, insertion, and testing," by F. D. Cotterman, N. A. Ziegler, and J. P. Magos. Crane Company, Contract OEMsr-629
A-409	6480	"The testing of erosion-resistant materials and the development of improved machine-gun barrels," by E. F. Osborn. Geophysical Laboratory, C.I.W., Contract OEMsr-51
A-410	6481	"Progressive centrifugal inmelting for the preparation of alloy tubes," by P. H. Brace. Westinghouse Research Laboratories, Contract OEMsr-915
		B. Chromium, Chromium Plating, and Chromium Alloys
A-78M	2082	"The preparation of chromium by the thermal decomposition of chromium iodide," by D. R. Mosher. Westinghouse Research Laboratories, Contract OEMsr-915
A-411	6482	"Chromium and chromium-base alloys as materials for gun liners," by P. H. Brace, J. F. Schairer, and N. A. Ziegler. Westinghouse Research Laboratories, Contract OEMsr-915
A-412	6483	"Experimental electroplating of gun barrels," by W. Blum, A. Brenner, and V. A. Lamb. National Bureau of Standards, Transfer of Funds from OSRD
A-413	6484	"An illustrated study of the effects of firing on chromium-plated bores of caliber .50 machine guns," by H. E. Merwin and M. Sullivan. Geophysical Laboratory, C.I.W., Contract OEMsr-51
A-414	6485	"Symposium on chromium-plating, Washington, D.C., May 14, 1943." Division 1, NDRC

C O N F I D E N T I A L

Report Number NDRC	OSRD	Title, Author, Contractor
A-415	6486	"Development of chromium-base hot-hard alloys as gun-liner materials," by R. M. Parke and F. P. Bens. Climax Molybdenum Company, Contract OEMsr-1273
		C. Stellite and Other Hot-Hard Alloys*
A-416	6487	"Stellite No. 21 as a material for gun liners — metallurgy and properties," by W. A. Wissler. Union Carbide and Carbon Research Laboratories, Contract OEMsr-1330
A-417	6488	"Studies of the application of stellite No. 21 to gun bores," by T. H. Gray and D. R. Mosher. Westinghouse Research Laboratories, Contract OEMsr-915
A-418	6489	"Investigation of certain methods for making gun linings of stellite and other erosion-resistant materials," by J. Wulff. Massachusetts Institute of Technology, Contract OEMsr-608
A-453	6524	"Production of stellite liners by centrifugal casting," by W. H. Shallenberger. Industrial Research Laboratories, Contract OEMsr-1424
A-447	6518	"Pilot plant for production of modified caliber .50 machine-gun barrels with stellite liners," by R. A. Mueller, F. D. Cotterman, and J. P. Magos. Crane Company, Contract OEMsr-1414
A-455	6526	"Production of modified caliber .30 machine-gun barrels with stellite liners," by M. M. Johnson, Jr. Johnson Automatics, Inc., Contract OEMsr-1433
A-463	6534	"Production of modified caliber .30 machine-gun barrels with stellite liners." Remington Arms Company, Contract OEMsr-1438
A-419	6490	"Preparation and testing of 37-mm stellite liners," by J. S. Burlew. Division 1, NDRC
A-420	6491	"Refractaloy 70 as a liner material for caliber .50 barrels," by T. H. Gray. Westinghouse Research Laboratories, Contract OEMsr-915
A-464	6535	"Hastelloy C as a liner material for machine-gun barrels," by F. S. Badger and W. A. Wissler. Haynes Stellite Company and Union Carbide and Carbon Research Laboratories, Contract OEMsr-1330
		D. Vapor-Phase Plating
A-421	6492	"Pyrolytic plating from the carbonyls of molybdenum, tungsten, and chromium," by L. H. Germer and J. J. Lander. Bell Telephone Laboratories, Contract OEMsr-1184
A-422	6493	"The semi-commercial preparation of molybdenum carbonyl," by A. L. McCoy. Climax Molybdenum Company, Contract OEMsr-1320
A-401	6472	"The synthesis of chromium hexacarbonyl," by B. B. Owen. Yale University, Contract OEMsr-1318
A-402	6473	"Pyrolytic plating of chromium from the vapor of chromium hexacarbonyl," by B. B. Owen. Yale University, Contract OEMsr-1318
		E. Molybdenum
A-423	6494	"Fabrication of molybdenum for use as a gun-liner material," by J. W. Marden. Westinghouse Lamp Division, Contract OEMsr-1205
A-424	6495	"Development of molybdenum for gun liners," by P. H. Brace. Westinghouse Research Laboratories, Contract OEMsr-915
A-425	6496	"Experiments on the melting of molybdenum," by F. Palmer. Climax Molybdenum Company, Contract OEMsr-1273; Westinghouse Research Laboratories, Contract OEMsr-915

*See also Report A-408 (OSRD-6479) listed under Group A.

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☐ REQUEST DOCUMENT(S) DESCRIBED BELOW BE REVIEWED TO DETERMINE WHETHER THEY CAN BE DOWNGRADED OR DECLASSIFIED AT THIS TIME. *(Include justification in the "REMARKS" section of this form.)*

☐ REQUEST APPROPRIATE CLASSIFICATION/REGRADING INSTRUCTIONS FOR DOCUMENTS DESCRIBED BELOW.

CONTROL NUMBER	DESCRIPTION *(TYPE, FILE REFERENCE, UNCLASSIFIED SUBJECT OR SHORT TITLE, INDORSEMENTS, INCLOSURES)*	CLASSIFICATION/ REGRADING INSTRUCTIONS OLD	NEW
ADC 059861	Behavior of gun liners and coatings tested under conditions of hypervelocity OSRD Rept No 6475, Oct 1945	C	U/L Dist. St. C
	13 Aug 2004 Per phone conversation with Mr. Joel Goldman, this item can be made Public Release Patricia Ays for Joel Goldman	U/L	U/U

PRINTED OR TYPED NAME AND TITLE OF OFFICER	SIGNATURE
PATRICIA AYS for Joel Goldman Librarian Chief, SSSAP Ofc.	Patricia Ays for Joel Goldman

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