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Study to Increase Gun Barrel Life by Plating the Bore With Tungsten

J. W. Gehring
K. H. Meyer
AC Electronics - Defense Research Laboratories

TECHNICAL REPORT AFATL-TR-68-124

OCTOBER 1968

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FOREWORD

This report was prepared by AC Electronics - Defense Research Laboratories, General Motors Corporation, Santa Barbara, California, under Contract F08635-68-C-0044 with the Air Force Armament Laboratory, Eglin Air Force Base, Florida. The report covers work done during the period January 1968 through October 1968. Mr. D. Davis (ATWG) and Mr. R. Blair (ATWG) were program monitors for the Air Force.

The program was performed under the supervision of J. W. Gehring with K. H. Meyer as the principal investigator. K. Stulpe conducted the metallurgical studies of the substrate preparation and the evaluation of the plating characteristics such as adhesion, interface strength, microstructure changes, grain size, hardness, etc. J. Lehner designed parts of and built the experimental apparatus and measured and evaluated the barrel bore before and after plating and test firing. Test firings were carried out by W. J. Martin, J. Lehner and D. Irby. The heat transfer computer study was done by D. Sangster.

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This technical report has been reviewed and is approved.

GEORGE P. BRENNER, Colonel, USAF
Chief, Weapons Division

ABSTRACT

A 0.004" oversized .220 cal rifled Swift gun barrel was plated with 0.002" of tungsten, thereby restoring its original bore size. The plated barrel and an unplated standard barrel were test fired with 1500 rounds of .220 caliber Swift Super Sport ammunition. This ammunition has a 48 grain projectile and was test fired at an average muzzle velocity of 3790 ft/sec with an average chamber pressure of 48,350 psi. The bore diameters as measured in both test barrels before firing and after firing 500, 1000 and 1500 rounds are listed in Tables II and III. As shown in these tables, less erosion was experienced over a shorter barrel length in the tungsten plated barrel than in the unplated barrel.

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SECTION I

PROBLEM: EROSION OF GUN BARRELS

Gun barrel bores deteriorate as the result of the firing of a large number of rounds depending on the following factors: pressure and temperature of propellant combustion end products during firing of a round, the firing rate and the resulting temperature of the gun barrel.

The mechanism of gun barrel deterioration consists essentially of the embrittlement of the surface layers of the gun barrel bore by the influence of hydrogen, nitrogen and carbon at the elevated pressure and temperature during propellant combustion. The chemical equation of combustion of the predominately nitrocellulose propellants, shows end products of a reducing nature:

$$2\ C_6H_5(OH)_2(NO_3)_3 \rightarrow 4\ CO_2 + 8\ CO + 6H_2O + H_2 + 3N_2 \qquad (1)$$

High pressures during the combustion cause compression and hoop tension stresses in the gun barrel tube; high temperatures cause differential thermal expansion between a thin surface layer and the depth of the metal, all resulting in crack formation, crack propagation and crack intersection. After a sufficiently large number of rounds, shear stresses induced in the surface by the friction between the bore surface and the passing projectile become large enough to remove some small fragments of the surface which are enclosed by two parallel pairs of intersecting surface cracks. The particle may be deposited at the edge of a land together with copper from the projectile mantle and may contribute to further erosion along the gun barrel bore. The most severely affected part of the bore is the section adjacent to the cartridge seat, which experiences the highest pressures and temperatures. A typical section of this portion is shown in Figure 1. The section has been made at a slight angle with the longitudinal axis. The left side shows the actual bore surface with a globular appearance; the right side shows surface cracks intersecting each other. Figures 2 and 3 show cross sections of a .30 cal unplated gun barrel after 500 rounds in the transverse and longitudinal directions.

Chrome plating of gun barrels is presently used to provide a hard bore surface and increased gun barrel life. Chrome plating however is porous and hot combustion gases react with the substrate gun metal through the porous surface and deterioration takes place as in an unplated barrel. Figure 4 shows the cross section of the bore surface of a chrome-plated barrel after 1200 rounds from which a small fragment has been removed. Figure 5 pictures an enlarged view of a surface crack and also some microhardness indentations and the hardness values of gun steel and chrome plating. Surface cracks in a section near the muzzle are indicated in Figure 6.

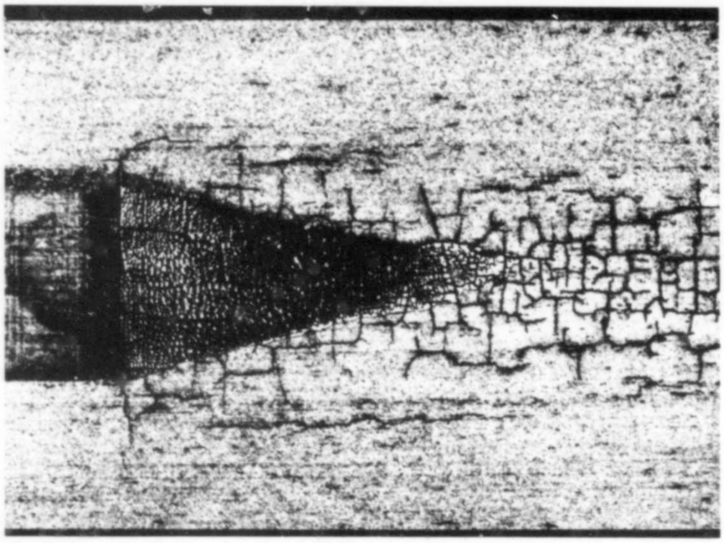

Figure 1. Surface of Inside of Chrome Plated .257 cal Gun Barrel Near Cartridge Seat (cut at slight angle to longitudinal axis), After 1200 Rounds - 12.7x

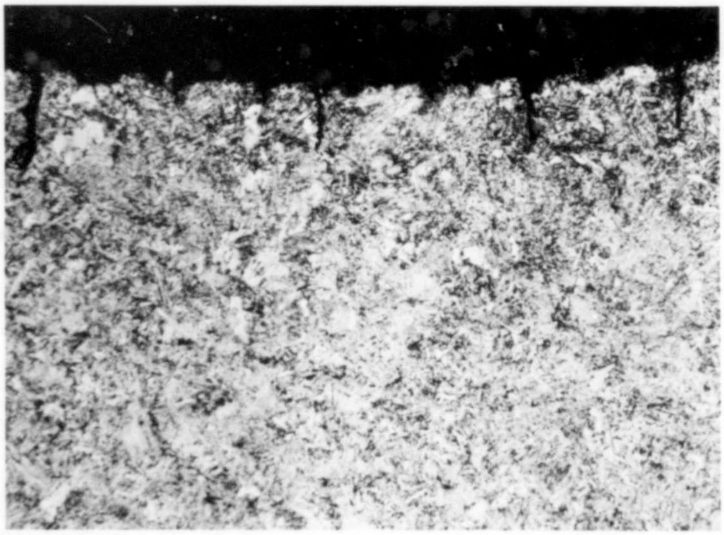

Figure 2. Cross Section of Inside of Unplated .30 cal Gun Barrel Near Cartridge Seat, After 500 Rounds - Transversal, 100x

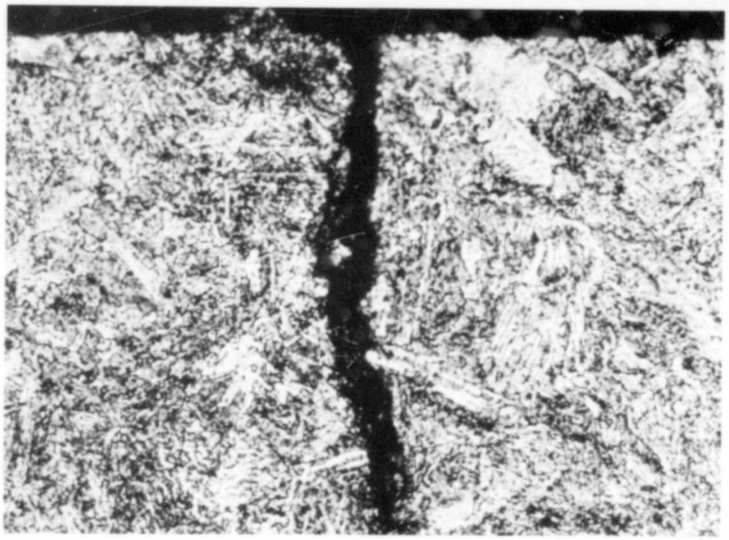

Figure 3. Cross Section of Inside of Unplated .30 cal Gun Barrel Near Cartridge Seat, After 500 Rounds – Longitudinal, 500x

Figure 4. Cross Section of Inside of Chrome Plated .257 cal Gun Barrel Near Cartridge Seat, After 1200 Rounds – Transversal, 100x

Figure 5. Cross Section of Inside of Chrome Plated .257 cal Gun Barrel near Cartridge Seat, After 1200 Rounds - Longitudinal, 500x

	DPH	R_C
Hardness, Hard Layer	946	68
Hardness, 4140 Steel	297	29.5

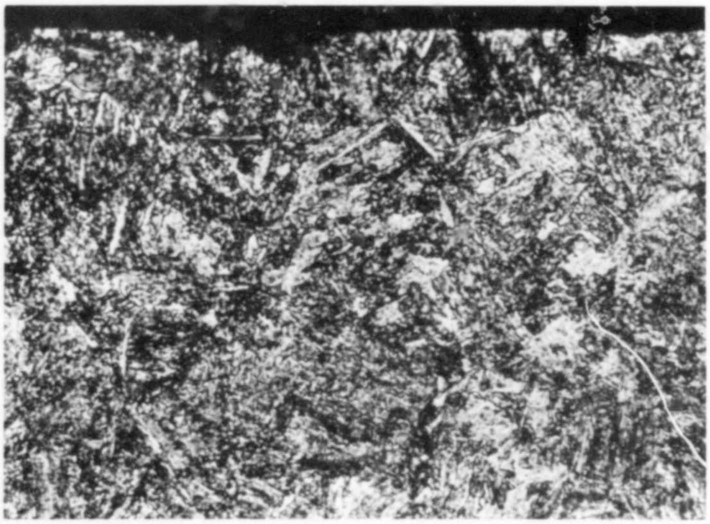

Figure 6. Cross Section of Chrome Plated .257 cal Gun Barrel Near Muzzle, After 1200 Rounds - Longitudinal, 500x

As a result of material erosion in the bore, propellant combustion gases escape between the projectile and the bore surface. This gas blow-by further increases projectile and barrel erosion and transports eroded particles along the bore where they are redeposited. This action leads to a decrease in the projectile muzzle velocity, the firing accuracy and reduces the effective range of the gun.

SECTION II

PROGRAM OBJECTIVE

The general objective of the program was to reduce the interaction of high-pressure, high-temperature combustion products with the gun metal, to reduce barrel erosion and to prevent a decrease in projectile muzzle velocity and accuracy.

The specific objective of the program was to plate the bore of .220 cal gun barrels with tungsten to increase the serviceable life of the barrel – that is, to increase the number of rounds which can be fired without increasing the bore I. D. beyond the acceptable limit.*

During the program .220 cal Swift barrels were plated at various plating thicknesses. These barrels were test fired using .220 Swift Super Sport ammunition. This ammunition has the highest muzzle velocity, 4110 ft/sec, among the standard small caliber munitions available and should bring about the most erosive effects with the minimum number of shots. The performance of the tungsten plated barrel was compared with a non-plated standard barrel by firing the same number of rounds under the same test conditions in each barrel.

The tungsten plating on the bore of the barrel should and did possess the following properties:

1. A good metallurgical bond between the substrate (4150 steel) and the tungsten plating.
2. A predetermined and uniform thickness of the tungsten plating along the entire length of the bore as well in the longitudinal as in the transverse directions.
3. Optimum physical and mechanical properties from the viewpoint of the operational life of the gun barrel. This includes the ability of the plating to withstand shockwave impacts at elevated temperatures, high-compression and shear stresses, and the corrosive influence of the propellant combustion products at high temperatures and pressures. The most important property of the plating is toughness or impact strength, meaning a compromise between high strength and ductility. To obtain these optimum properties in

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* P. R. Landry and C. E. Nilsson, "Barrel Erosion Study of Rifles, 5.56 mm, M16 and XM16E1, A Joint Army-Air Force Test," SA TR11-5000, Springfield Armory, Springfield, Mass., January 1966.

the tungsten plating, deposition parameters such as temperature, the ratio of tungsten hexafluoride over hydrogen, and flow rates can be varied within certain limits.

SECTION III

PROPERTIES OF TUNGSTEN

The selection of the metal tungsten was made because of its outstanding mechanical and physical properties:

1. Tungsten has the highest melting point of all known metallic elements. MP = 6170°F (3410°C).
2. Tungsten retains a substantial amount of strength above 2000°F. Ultimate Tensile Strength of Commercial Tungsten at 2400°F: 45,000 psi.
3. Pure tungsten has the lowest thermal expansion coefficient of all metals ($2.2 - 6.3 \times 10^{-6}$ in./in./°F) depending on history.
4. Strength, hardness and toughness of vapor deposited tungsten can be varied over a wide range depending on deposition parameters such as temperature, WF_6/H_2 flowrate and ratio. Hardness range of VPP Tungsten R_C40 - 60 (DPH 393–695).
5. Tungsten has one of the highest thermal conductivities (31.5–96.9 BTU/hr/ft^2/°F/ft).
6. Tungsten has the lowest compressibility of any known metals (0.28×10^{-6}/megabar).
7. Tungsten has one of the highest moduli of elasticity in tension (59×10^6 psi).

A comparison of the mechanical and physical properties of tungsten and 4150 gun steel are listed in Table I. The mechanical and physical properties of tungsten listed in the literature vary considerably depending on the type of manufacture (pressed and sintered powder, arc cast, etc.) or thermal history.

TABLE I. MATERIALS PROPERTIES

	Tungsten ** Comm. Pure.	Gun Steel*** 4150
Density g/cm^3 (lb/in.^{3})	19.3 (0.70)	~7.8 (.28)
Impact Str. (Charpy) kg-m (ft-lb)		1.4 (10)
Tens. Yield Str. kg/cm^2 (ksi)	15500 (220)	8930 (127)
UTS kg/cm^2 (ksi)	15500 (220)	9910 (141)
Elongation (%)	0–95	19
Red. of Area (%)	0–46	56
Melting Point (^{o}C)	3410	~1510
Melting Point (^{o}F)	6170	~2750
Spec. Heat C_p (cal/g/^{o}C)	0.033	0.10–0.11
Spec. Heat (BTU/lb/^{o}F	0.033	0.10–0.11
Therm. Cond. (cal/cm^2/cm/^{o}C/sec)	~0.40	~ 0.1
Therm Cond. (BTU/hr/ft^2/^{o}F/ft)	~31.5, 96.9	~8
Coeff. of Thermal Exp. (^{o}Cx10^{-6})	~ 4.5	~11
Coeff. of Thermal Exp. (^{o}Fx10^{-6})	~2.5	~ 6
Hardness R_C (DPH)	Plating 40-60 (393-695)	30 (301)
Coeff. of Friction μ_s (μ_k)*		0.58
Hemispherical Total Absorptance α	RT 0.022, 1800^{o}C 0.27	RT ~0.50
Atom Diameter (Å)	2.82	2.52
Crystal Structure	BCC, Cub. Diam.	BCC,
Ductile-Brittle Trans.	(VPP) 130–270 (265–510)	540–815 (1000–1500)
Recrystallization Temp. ^{o}C (^{o}F)	> 1260 (>2300)	> 840 (>1550)
Cost ($/lb)	2.00–40.00	0.50
Heat of Form. of Oxide (kcal/mol)	WO_2 130.5	Fe_2O_3 198.5
Velocity of Sound (10^{3}ft/sec)	14.0	16.7

* Against same material (steel against bronze 0.12)
** Tungsten properties vary in literature depending on preparation and thermal history
*** 4150 steel mechanical properties given for "as forged" condition.

SECTION IV

DESCRIPTION OF THE VAPOR PHASE PLATING PROCESS OF TUNGSTEN

Since tungsten cannot be plated electrolytically as a coherent coating, the vapor phase plating process is utilized to obtain a dense nonporous plating with good adhesion to the substrate.

A modification of the basic process has been developed at AC Electronics - Defense Research Laboratories producing a firm bond on 4150 gun steel. In the process a mixture of tungsten hexafluoride (WF_6) and hydrogen is brought into contact with the specimen at a temperature between 600°F and 1200°F. Within this temperature range a reaction between WF_6 and hydrogen takes place according to the equation:

$$WF_6 + 3\,H_2 \rightarrow W + 6\,HF \tag{2}$$

The tungsten is reduced by the hydrogen from its hexavalent state to the elementary form and deposits on the hot substrate as a metallic film of high density. The adherence of the film is determined by the surface preparation of the substrate such as degreasing, treatment with a mixture of acids, and removal of the etching products. The deposition takes place in the experimental apparatus shown in Figure 7. A basic schematic diagram of the process is shown in Figure 8.

During the process it is very important to keep out traces of air oxygen and water vapor. These elements react with tungsten hexafluoride in an undesirable side reaction forming tungsten oxide in the form of a blue film on the substrate surface and preventing a good bond from forming, as well as causing flaking of the tungsten plating. The equations of these side reactions are:

$$WF_6 + 3\,H_2O \rightarrow WO_3 + 6HF \tag{3}$$

$$2WF_6 + 3O_2 \rightarrow 2WO_3 + 12HF \tag{4}$$

The mechanical and physical properties of the vapor deposited tungsten should represent a compromise between high strength and high hardness on one hand, and a large elongation (ductility) on the other, resulting in a good impact strength (toughness) and erosion resistance under the environmental conditions existing in the gun barrel bore during firing of a round. To obtain these desired properties, the deposition parameters such as temperature, tungsten hexafluoride and hydrogen flowrates and ratios can be varied to obtain tungsten plating for example in the hardness range between $R_C 40$ and 60.

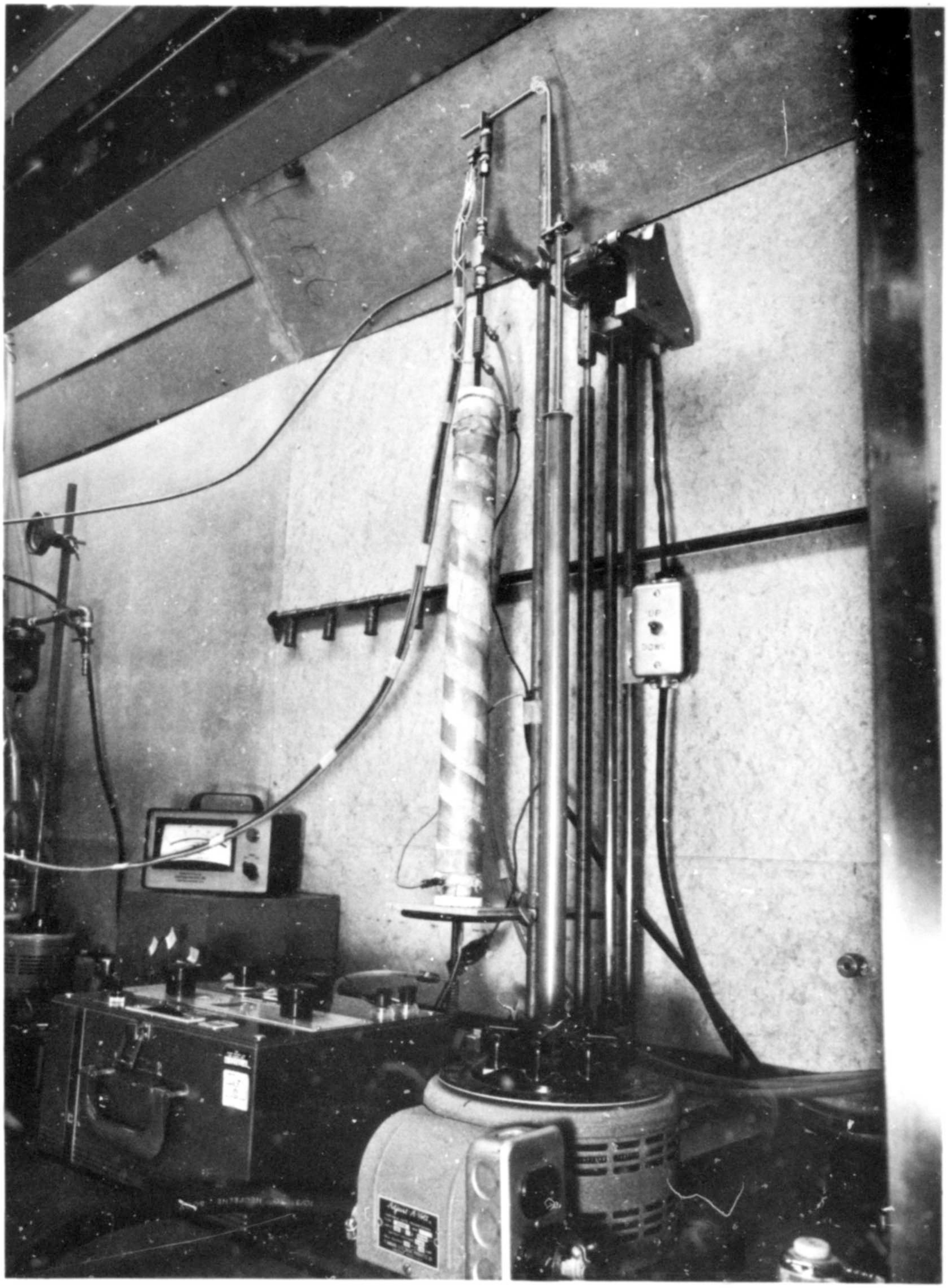

Figure 7. Gun Barrel Plating System with Moving Nozzle

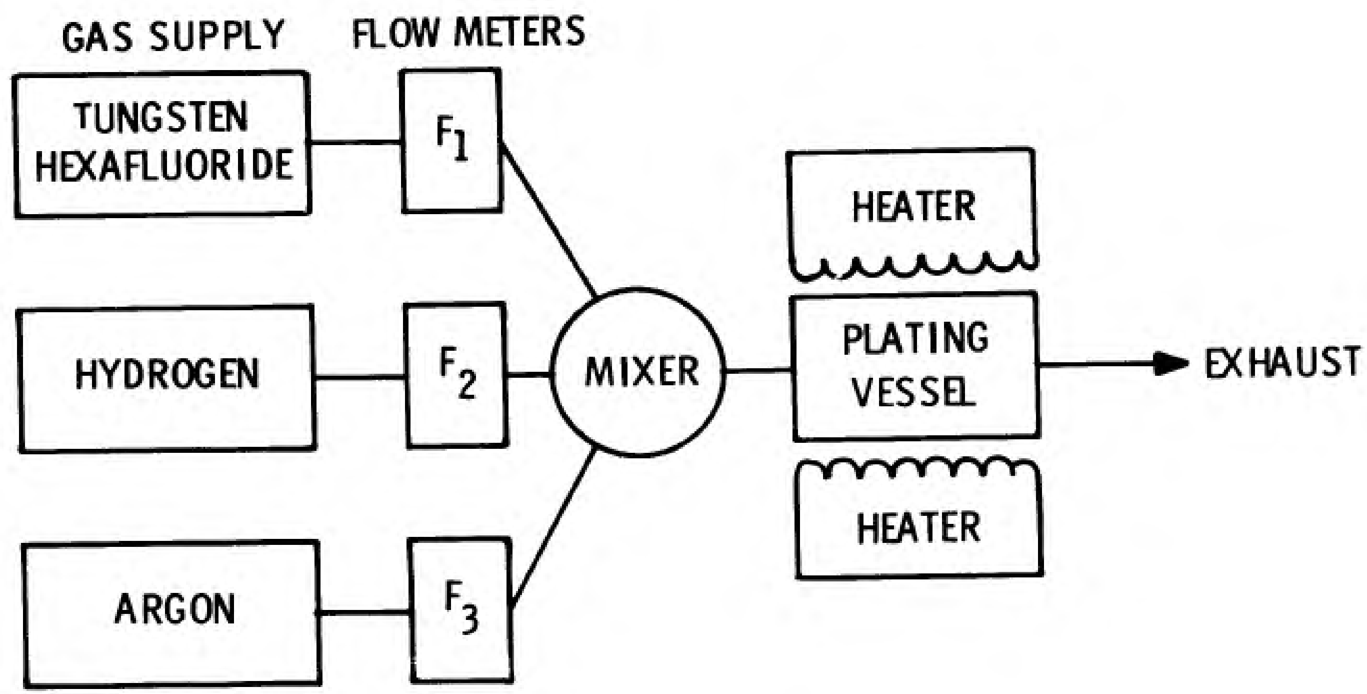

Figure 8. Schematic Flow Diagram for Vapor-Phase Plating Process

SECTION V

REQUIREMENTS FOR DIMENSIONS AND PROPERTIES OF GUN BARREL BORE AND TUNGSTEN PLATING

Since the tungsten plated bore must have the same inner diameter as the standard bore, the barrel before plating must be oversize by the intended thickness of the tungsten plating, e.g., a .220 cal barrel with .224 groove must have a .224 bore and .228 groove, so that a plating thickness of 0.002" will restore the original bore size. Barrel blanks which were oversized by 0.002", 0.004" and 0.008" were therefore ordered custom-made to the specified dimensions to be plated with tungsten thicknesses of 0.001", 0.002" and 0.004" respectively.

The tungsten plating must have a predetermined and uniform thickness within ±0.0001" in the longitudinal and transversal directions and on top of the bore as well as at the bottom of the groove and must be following the contours of the rifling closely.

To fulfill this requirement, the tungsten thickness is limited to a few thousandths of an inch, otherwise the edges of the rifling will be rounded off after plating and will be covered with a larger thickness of tungsten than the grooves, so that subsequent re-rifling would be necessary. Re-rifling of the tungsten plating would require special high hardness tools.

SECTION VI

TUNGSTEN PLATING OF GUN BARRELS, EXPERIMENTAL APPROACH

To obtain a tungsten plating fulfilling the requirements listed in the previous section, a large number of experimental plating runs were conducted. For these test runs a small convenient test specimen was selected in the form of thin tube sections of 0.5" length and 5/15" outside diameter of 4130 steel (see Figure 9). The inside diameter was close to the bore size of a .22 cal gun barrel. A number of test runs were conducted using these tube sections and varying etching and cleaning methods, deposition temperatures, and WF_6/H_2 flow rates and ratios, until the optimum plating and bond between tungsten and substrate had been obtained. The conditions selected resulted in a tungsten hardness of approximately $R_C 46$, for a plating thickness of 0.002".

After the deposition parameters for the optimum bond and tungsten properties were established, 5/16" 4130 tubing of a length comparable to the .22 cal gun barrel was utilized to establish the conditions for plating a tungsten coating of predetermined (0.002") and uniform (± 0.0001") thickness in the longitudinal as well as in the transverse directions. This was done by means of the resistance heating furnace and the moving nozzle arrangement shown in Figure 7. After these conditions were established – in the form of a uniform temperature of the 4130 tube (obtained by means of six separate heating elements), the speed of the traveling nozzle, and the WF_6/H_2 flow rates and ratio – finally an actual .220 cal Swift gun barrel blank of 1.0" outside diameter was plated. The barrel blank to be plated with threads, fittings and copper gaskets is shown in Figure 10. A spent .220 Swift cartridge is used to mask the chamber area from plating. The thread at the end of the barrel blank also fits the universal receiver and a Winchester Type 70 action used for subsequent test firing and shown in Figure 11. A heating experiment under argon was conducted to establish voltages for the six heating elements to obtain a uniform temperature distribution along the barrel. Then, an actual plating run was conducted, and a plated barrel with a tungsten thickness slightly larger than 0.002 in. was obtained. After honing the surface of the plating to the nominal inner diameter of 0.220" by means of a honing tool shown in Figure 12, test firings were conducted.

After about 10 rounds severe flaking of the tungsten plating was observed. As a result of the flaking, test conditions were changed in the next run and a liquid nitrogen trap and a catalytic cartridge were added to the system to eliminate all possible traces of oxygen and water vapor from the system. After a number of experiments another plated barrel was

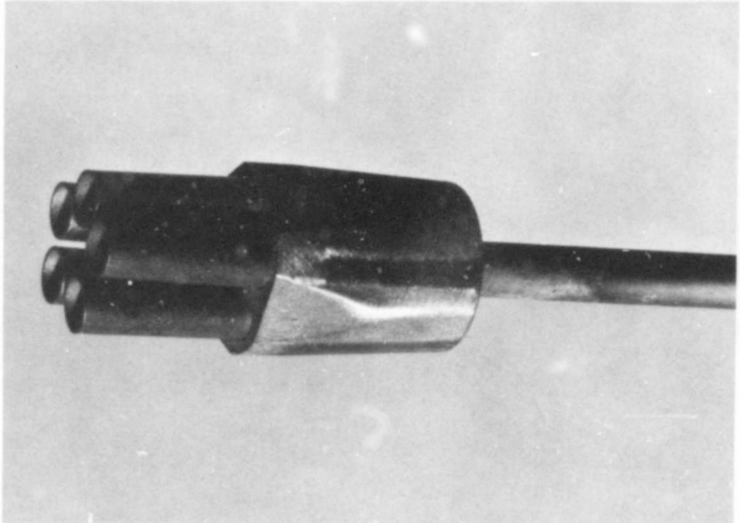

Figure 9. Tube Specimen of 5/16 in. 4130 Steel on Specimen Holder

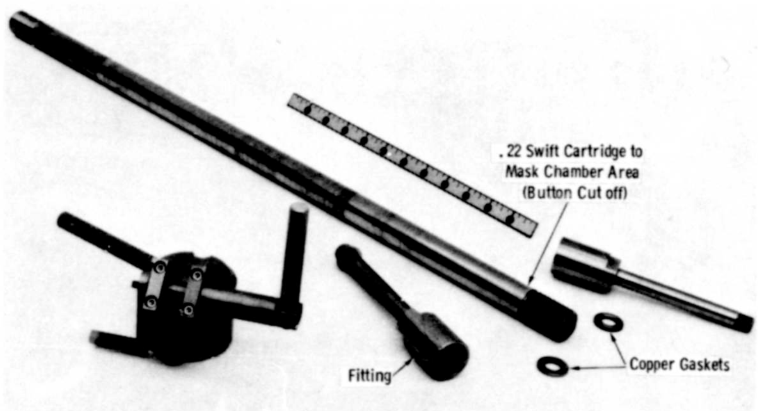

Figure 10. .22 Cal Gun Barrel with Threads for Gas Fittings or Universal Receiver

Figure 11. Universal Receiver and Winchester 70 Action on .220 Swift Gun Barrel Blanks

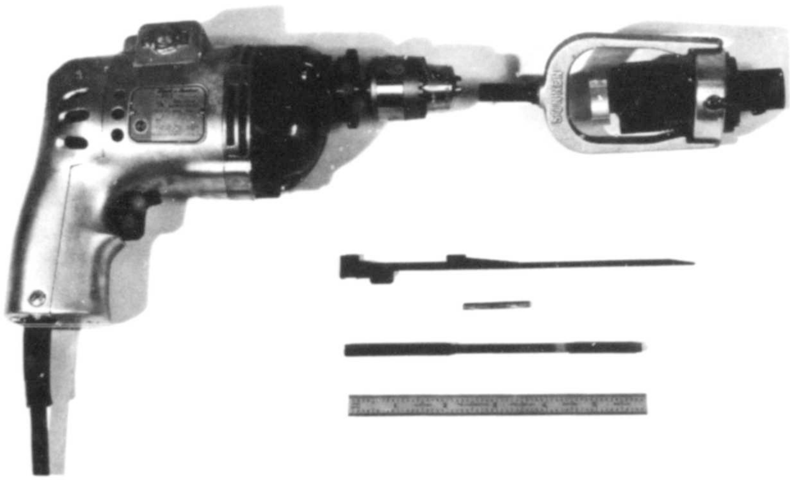

Figure 12. Honing Tool for Tungsten Plated .220 Cal Gun Barrel

obtained. A 2 in. test specimen was cut from the muzzle for sectioning and metallurgical examination. Figure 13 shows part of a transverse cross section of the .220 cal Swift barrel bore plated with 0.002 in. of tungsten at a magnification of 100x. Figure 13 also shows how closely the plating follows the contour of the rifling and that the plating thickness is uniform on top of the lands and at the bottom of the rifling.

Figure 14 shows another cross section with microhardness indentations indicating a hardness of R_C46 for the tungsten plating and $R_C25.5$ for the 4150 steel. In Figure 15 microhardness indentations in the interface under loads of 2000 gm, 1000 gm and 500 gm respectively from left to right were made to test the adhesion of the tungsten plating to the 4150 steel substrate. Figure 16 is a photograph of the interface between tungsten and steel at a magnification of 1000x.

Figures 14 and 15 also show that the tungsten plating consists of columnar crystals growing in a direction normal to the substrate surface. The columnar crystals start to grow from a microcrystalline deposit on the surface. With the increasing thickness of the plating some of the smaller crystals disappear and the diameter of the larger crystals increases. With the increasing grain size the hardness decreases. The columnar crystals grow in the form of pyramids on the surface as shown by an electron scanning micrograph in Figure 17. The distance between the tips of the pyramids and their base is approximately 0.0002 in. This surface roughness is being removed from the surface of the lands by honing to obtain a smooth surface with minimum friction between bore and projectile.

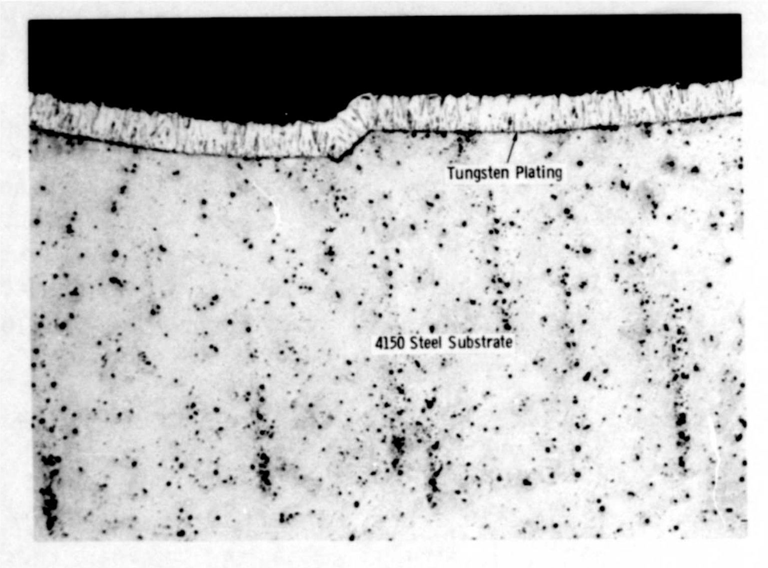

Figure 13. Transverse Cross Section of .220 Swift Gun Barrel Bore Plated with 0.002 in. of Tungsten Before Honing (100x)

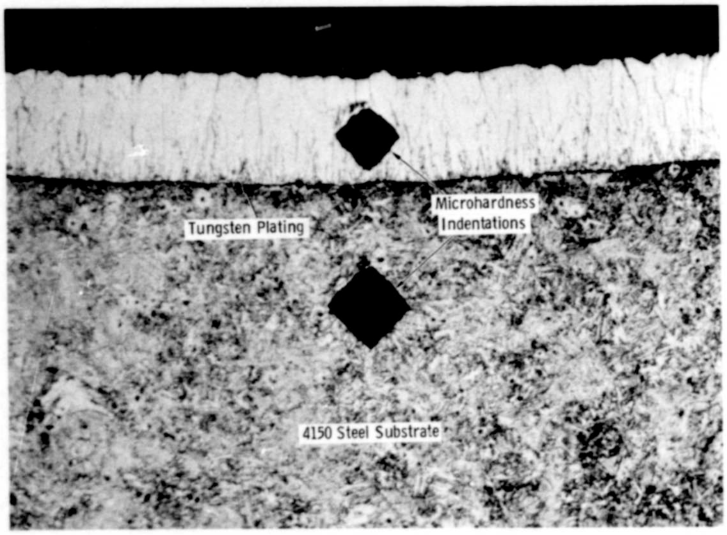

Figure 14. Transverse Cross Section with Microhardness Indentations Under 500g Load (200x) (Before Honing)

	Diamond Pyramid Hardness	Rockwell C. Hardness
Tungsten	458	46.0
4150 Steel	266	25.5

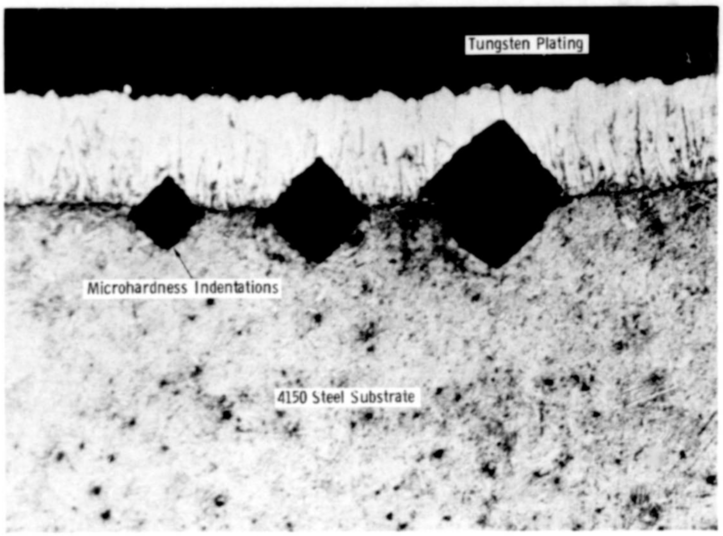

Figure 15. Transverse Cross Section with Microhardness Indentations under 500g, 1000g, 2000g Load on Interface to Show Quality of Bond Between Tungsten and Steel (200x) (Before Honing)

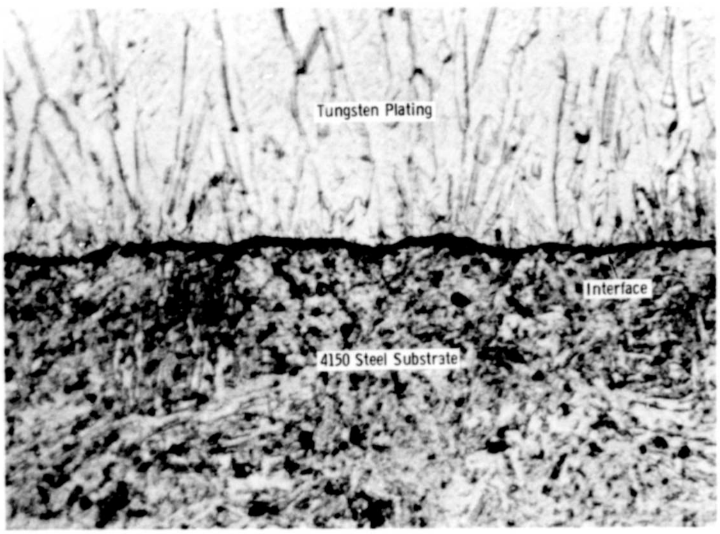

Figure 16. Transverse Cross Section Showing Interface Between Tungsten and Steel at 1000x

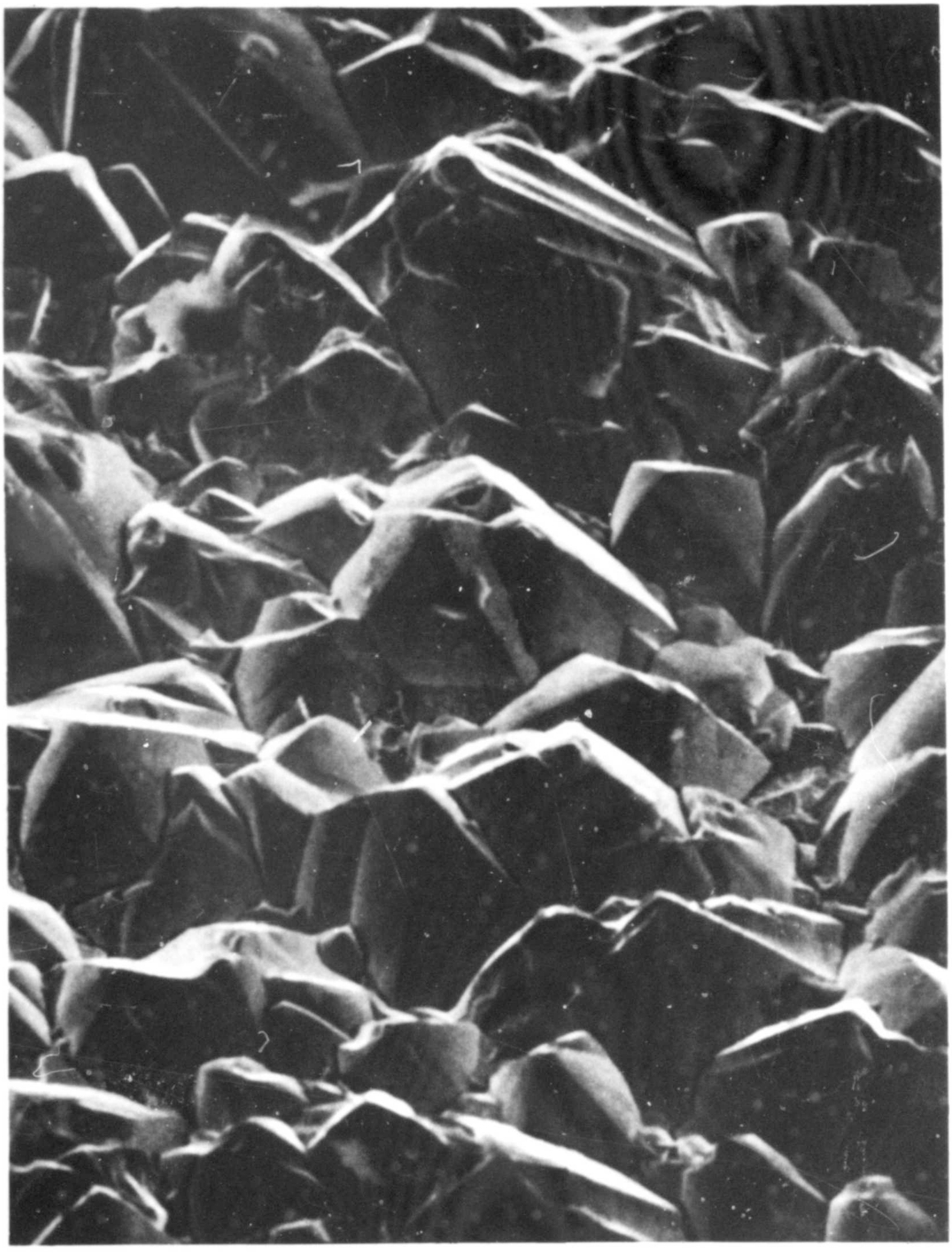

Figure 17. Electron Scanning Micrograph of the Surface of Vapor Phase Plated Tungsten. Distance Between Tips and Bases of Pyramids Approx. 0.0002 in. (600x)

SECTION VII

INVESTIGATION OF THE TUNGSTEN-STEEL INTERFACE

After a good bond had been obtained by empirical means - that is by variation of the deposition parameters - it was of interest to know the exact dimension and composition of an interface associated with a good bond and to determine the requirements for a good bond. It was known that oxide films and other contaminations had to be avoided, that a minimum amount of diffusion of the two metals into each other was required, and it was assumed that hydrogen embrittlement was detrimental to a good bond.

To obtain more information about the interface, various instrumental methods were applied. Optical microscopy at high magnifications is limited in the information it provides. To obtain a detailed image of the microscopic structure in and near the interface it is necessary to remove the top layer of the polished surface by etching. Etching however always produces a groove by galvanic action between the two metals of the interface and this groove can not be imaged very well because of the limited depth of field of the optical microscope. The groove appears in the optical micrograph as a black line, the width of the line being a function of the concentration of the etchant and the duration of etching (refer to Figures 12 to 16). Figure 17 is an electron scanning micrograph which shows the surface of vapor phase deposited tungsten. The pyramid-like structure has a distance of approximately 0.0002 in. between the tips and the bases. An electron micrograph (Figure 18) shows the depth of the interface between tungsten and 4150 steel and some detail of the area adjacent to the interface.

To complement this information, scans were taken of the interface by an electron probe microanalyzer. Three scans were made across the interface with the detectors of the instrument set for three different pairs of elements using a recording of the specimen current as a reference trace in each scan. These pairs of elements are: Iron vs tungsten, oxygen vs iron and nitrogen vs tungsten (Figures 19 to 22). The scan of iron vs tungsten shows how the concentration of iron (distance from the top edge of the chart) decreases while the concentration of tungsten (distance from bottom edge of chart) increases slowly. The specimen current increases and decreases during the scan across the interface with the concentration changes of iron and tungsten, and indicates a depth of the interface of approximately 9μ ($\sim$0.0003 in.) (Figure 19). The scan for oxygen versus iron (Figure 20) was taken to determine whether any oxygen film was left in the interface. The oxygen line does not go above the background level in the recording, indicating a lack of an appreciable amount of oxide in the interface. A third scan was taken for nitrogen versus tungsten (Figure 21) to determine a residue of nitrates (the etchant contains nitric acid) which also turned out negative.

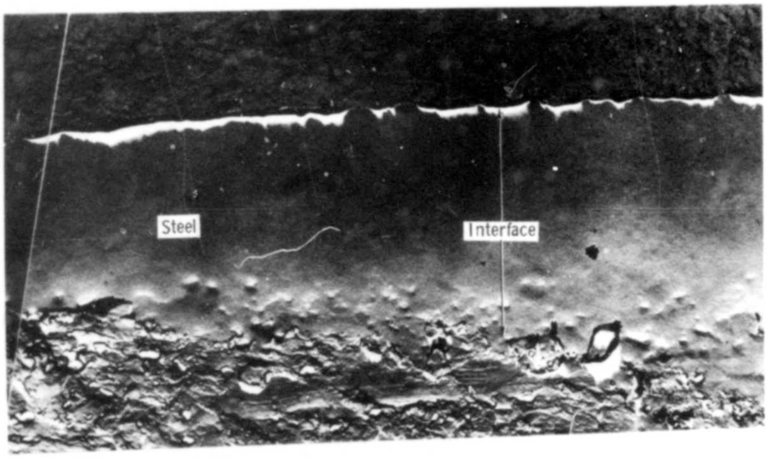

Figure 18. Electron Micrograph of Two Stage Replica with Shadowcast Showing Interface Between Tungsten and 4150 Steel (12,500x)

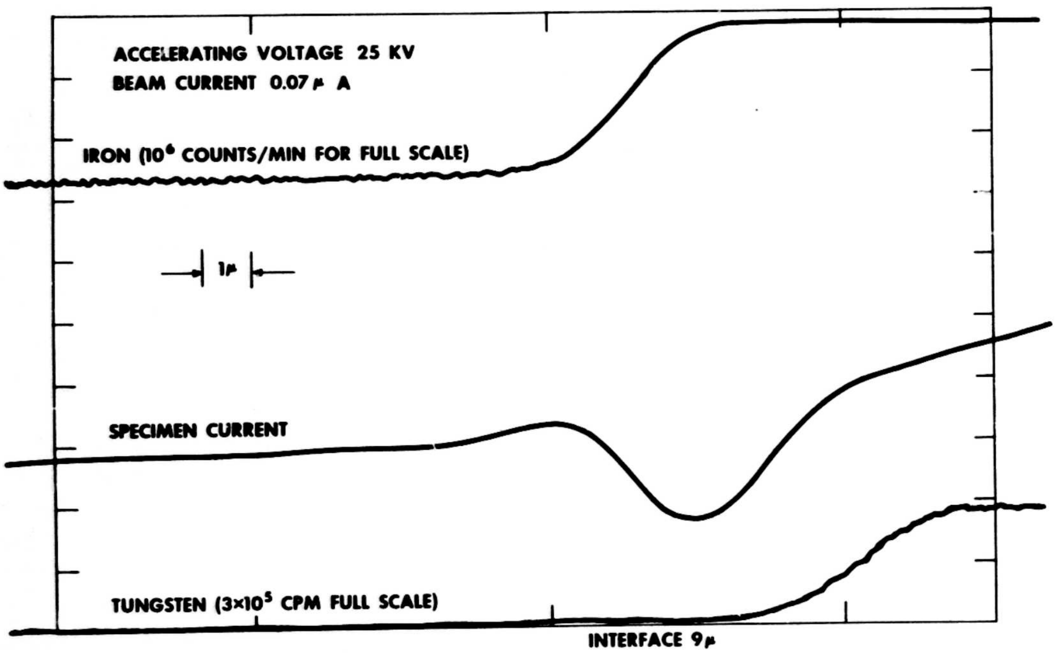

Figure 19. Electron Microprobe Scan of Iron vs Tungsten

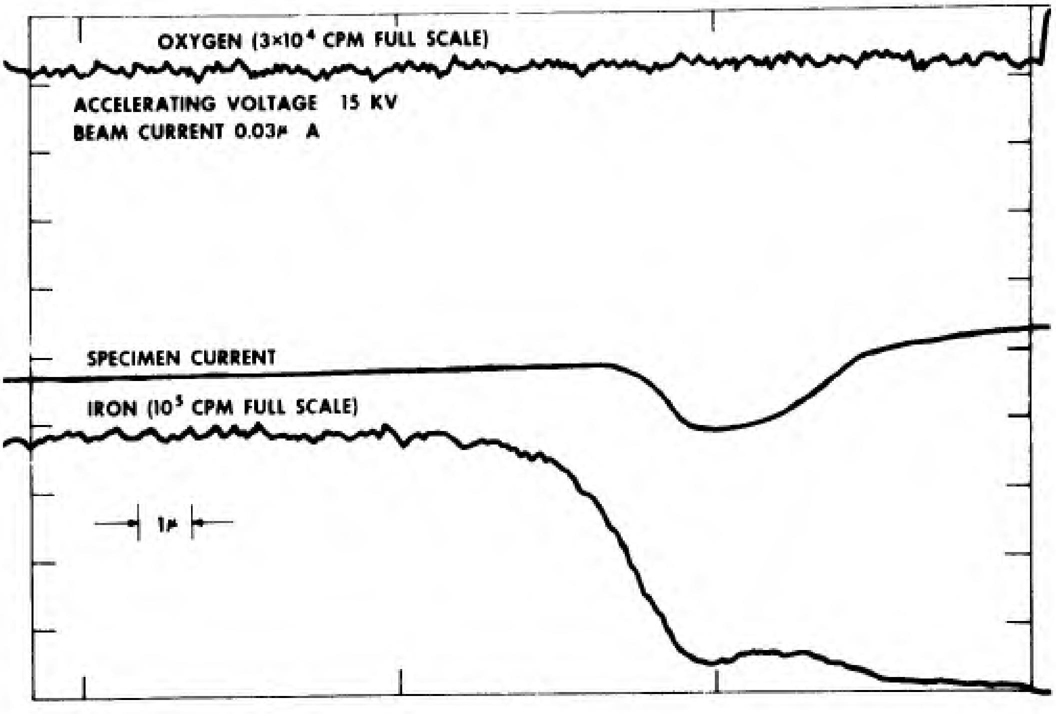

Figure 20. Electron Microprobe Scan of Oxygen vs Iron

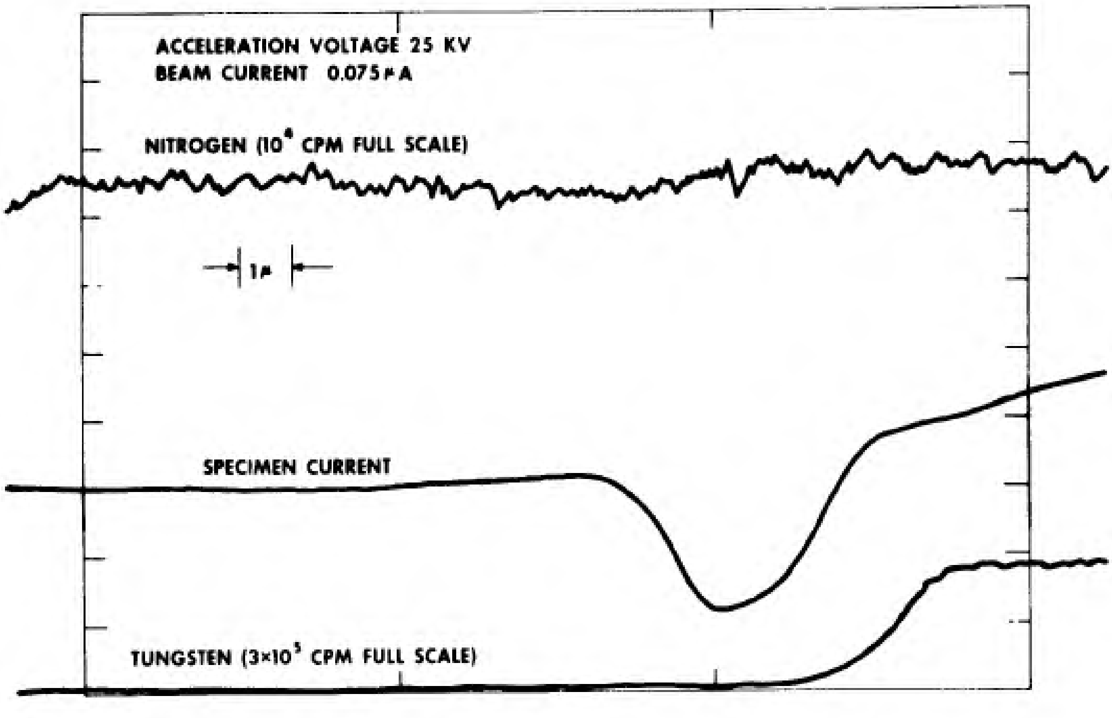

Figure 21. Electron Microprobe Scan of Nitrogen vs Tungsten

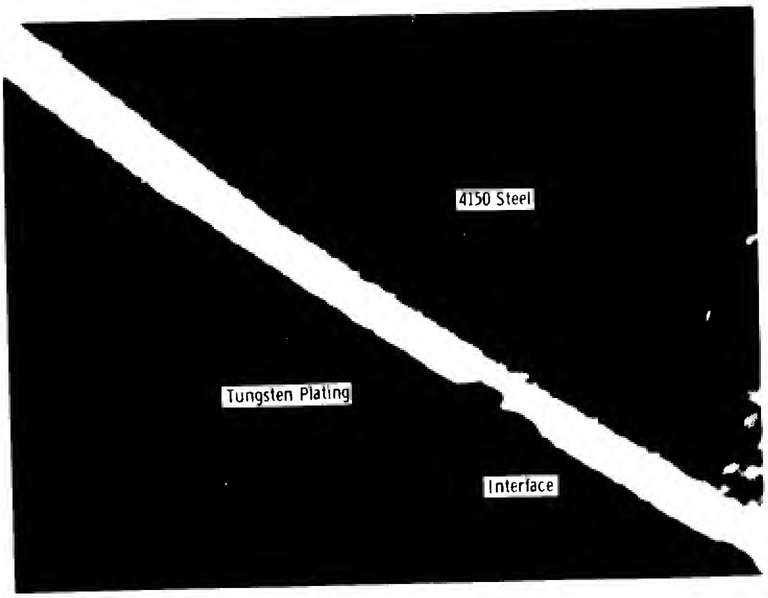

Figure 22. Electron Emission Image of Interface Between Tungsten and 4150 Steel

In addition to the electron probe scans, an electron emission image is shown in Figure 22 which corresponds to a low resolution scanning electron micrograph and shows the interface between tungsten and steel. The instrumental methods applied give the following information about conditions associated with a good bond between vapor phase plated tungsten and 4150 gun steel:

a. A diffusion zone between tungsten and steel of approximately 5 to 10μ depth.
b. A tungsten hardness of about R_C46 (diamond pyramid hardness 458).

These conditions do not necessarily represent the optimum case; additional detailed investigations into the correlation between depth of interface and significance of hydrogen embrittlement on one side and the quality of the bond and the properties of the deposited tungsten on the other side are required.

SECTION VIII

TEST FIRING OF A TUNGSTEN-PLATED AND AN UNPLATED GUN BARREL

For the test firing of the plated and unplated gun barrels, the .220 cal Swift cartridge was chosen, since this round has the highest muzzle velocity of all commercially available .22 cal cartridges, and with it the highest chamber pressure and temperature. This means that deterioration of the plated as well as the unplated gun barrel takes place after a smaller number of rounds than with other cartridges. The two barrels were fired for 1500 rounds, each under exactly the same conditions with regard to firing rate, etc. The only difference was that the plated barrel was two inches shorter since a test specimen was cut off for metallurgical inspection. The inner diameter of the bore of both barrels was measured by split-ball gauge (Figure 23), first after each shot, then in increasingly larger intervals.

The I. D. measurements after 500, 1000 and 1500 rounds are listed in Tables II and III, with the numbers in the first column indicating the distance of the diameter from the breech. The bore diameters indicate that the unplated barrel is eroded to a larger degree and over a longer distance down the barrel. The test firing had to be stopped at that point because of lack of ammunition. These tests will be continued, however.

At regular intervals the muzzle velocities were measured using ballistic screens and the chamber pressures were recorded by Kistler gauges with the data listed in Tables IV through VII. Controlled accuracy firings were conducted in a light gas gun range and are listed in Table VIII. The corresponding target cards are shown in Figure 24. A photograph of a flying .220 Swift projectile was taken and is pictured in Figure 25. A P/T measurement was made using a Kistler gauge and was recorded on an oscillogram shown in Figure 26. The test firing was carried out in AC-DRL's Terminal Ballistics Laboratory. A typical test fixture is displayed in Figure 27.

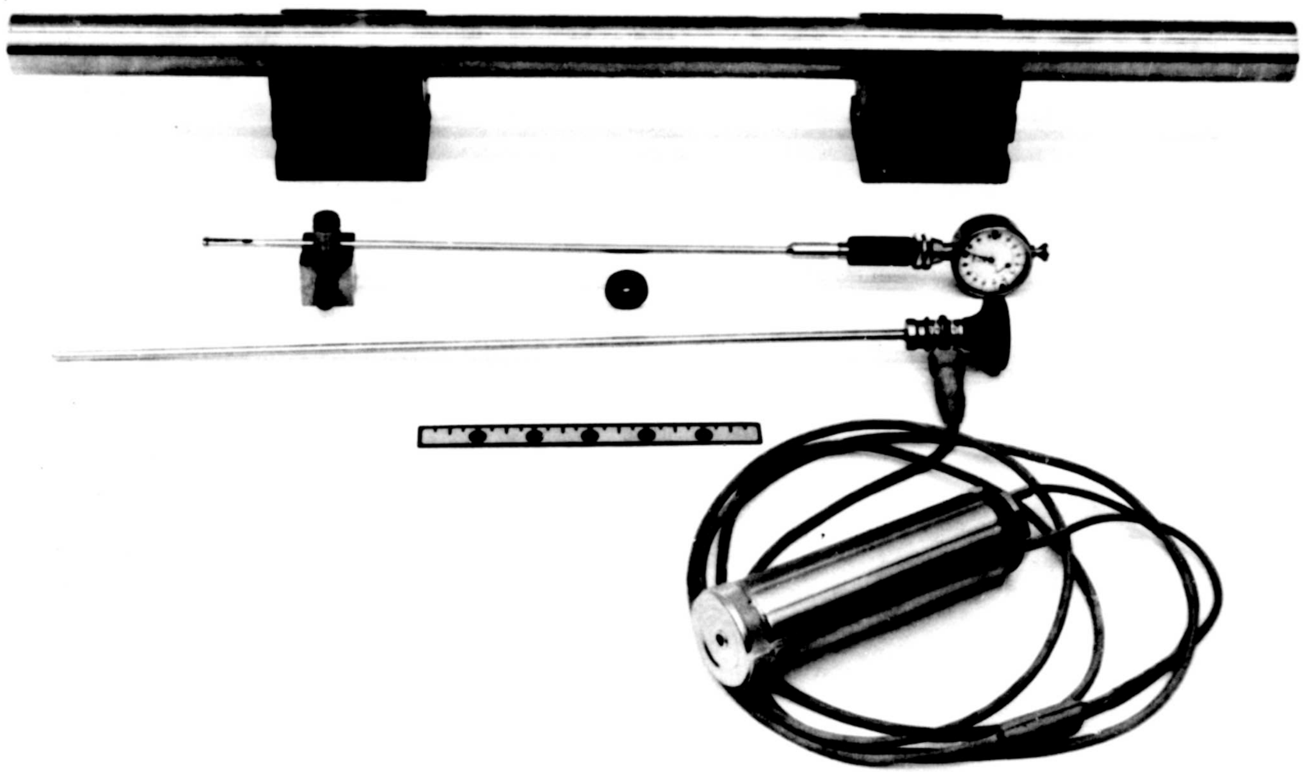

Figure 23. Split-Ball Gauge and Borescope for I. D. Measurement and Inspection of .22 cal Gun Barrels

TABLE II. RESULTS OF TEST FIRING OF TUNGSTEN-PLATED .220 SWIFT BARREL G (VPP 101), LENGTH 25.25" (AFTER CUTTING OFF TEST SPECIMEN AT MUZZLE) INNER DIAMETER OF BORE (in.)

Distance from Breech	Before Firing	After 500 Rounds	After 1000 Rounds	After 1500 Rounds	Difference Before and after 1500 Rounds
0					
1					
2					
2 1/4	.2204	.2215	.2217	.2245	+.0041
2 1/2	"	.2202	.2199	.2219	+.0015
2 3/4	"	.2204	.2200	.2212	+.0008
3	.2203	.2205	.2196	.2202	-.0001
3 1/4	"	.2204	.2202	.2203	.0000
3 1/2	"	.2204	.2203	.2203	.0000
3 3/4	"	.2204	.2202	"	.0000
4	.2203	.2204	.2202	.2204	+.0001
4 1/2	"	"	"	"	+.0001
5	.2203	.2204	.2202	"	+.0001
6	.2203	.2204	.2201	"	+.0001
7	.2204	.2205	.2203	"	.0000
8	.2204	.2204	.2200	"	.0000
9	.2204	.2203	.2201	"	.0000
10	.2204	.2204	.2200	.2203	-.0001
11	.2204	.2205	"	.2204	.0000
12	.2204	.2205	.2202	"	.0000
13	.2204	.2205	.2201	"	-.0000
14	.2204	.2205	.2202	"	.0000
15	.2204	.2205	"	"	.0000
16	.2204	.2205	.2203	"	.0000
17	.2202	.2203	.2201	.2203	+.0001
18	.2201	.2202	.2200	"	+.0002
19	.2201	.2202	"	.2201	.0000
20	.2201	.2202	.2201	.2202	+.0001
21	.2201	.2202	"	"	+.0001
22	.2196	.2220	.2199	.2200	+.0004
23	.2196	.2198	.2196	.2199	+.0003
24	.2199	.2199	.2199	.2202	+.0003
25	.2201	.2201	.2195	.2212	+.0011

TABLE III. RESULTS OF TEST FIRING OF UNPLATED .220 SWIFT BARREL B, LENGTH 27.25" INNER DIAMETER OF BORE (in.)

Distance from Breech	Before Firing	After * 434 Rounds	After 1000 Rounds	After 1500 Rounds	Difference Before and after 1500 Rounds
0					
1					
2					
2 1/4	.2202	.2230	.2242	.2253	+.0051
2 1/2	.2203	.2215	.2234	.2240	+.0037
2 3/4	.2202	.2208	.2221	.2231	+.0029
3	.2202	.2205	.2215	.2223	+.0021
3 1/4	"	.2201	.2209	.2216	+.0014
3 1/2	"	.2200	.2208	.2211	+.0009
3 3/4	"	"	.2206	.2208	+.0006
4	"	.2201	.2205	.2206	+.0004
4 1/2	"	.2202	.2203	.2204	+.0002
5	.2202	"	"	"	+.0002
6	"	.2204	.2204	.2205	+.0003
7	"	"	"	"	+.0003
8	"	.2203	"	"	+.0003
9	"	.2202	"	"	+.0003
10	.2202	.2202	"	"	+.0003
11	"	.2203	.2205	"	+.0003
12	"	"	"	"	+.0003
13	"	.2204	.2206	.2207	+.0005
14	"	.2204	"	"	+.0005
15	.2201	.2204	"	"	+.0006
16	"	.2204	.2205	.2205	+.0004
17	"	.2204	"	.2206	+.0005
18	"	.2204	"	.2206	+.0005
19	"	.2204	"	.2206	+.0005
20	.2202	.2205	"	.2205	+.0003
21	"	.2204	"	.2206	+.0004
22	"	.2204	"	"	+.0004
23	"	.2205	"	.2207	+.0005
24	"	.2198	"	.2207	+.0005
25	.2198	.2198	.2199	.2207	+.0009
26	"	.2205	.2205	.2207	+.0009
27	.2202	.2202	.2205	.2207	+.0005

*After 200 rounds appearance of cracks across bore and grooves

TABLE IV. TUNGSTEN-PLATED BARREL

FIRING RECORD

TEST NO.__________
JOB NO. 03-28210-000

AMMUNITION: Remington -.220 Swift - Index 0822

Case:	Used X:	Catalog No.:
Primer:	Loader: Remington	Lot No.: J03Y
Powder: gr.	On:	Seating Depth:
Bullet: 48 gr.		Overall Length:
WEAPON: V.P.P. #101	Ser. No.: G	Bbl. Length: 25.25"
Bore: Groove:	Number:	Twist:

Round No.	VELOCITY Time Over 5 ft.	f.p.s. @	PRESSURE Loc Lc	p.s.i.	REMARKS
					#400 Kistler
1	1316 usec	3799		55,000	
2	1356	3687		50,000	
3	1337	3740		50,000	
4	1314	3805+		52,000	
5	1315	3802		54,000	
6	1360	3676		49,000	
7	1345	3717		49,000	
8	1335	3745		50,000	
9	1361	3674		46,000	
10	1341	3729		50,000	
11	1346	3715		51,000	
12	1365	3663		45,000*	Cartridge case hole not centered
13	1379	3626		46,000	
14	1350	3704		50,000	
15	1332	3754		50,000	
16	1346	3715		48,000	
17	1369	3652		47,000	
18	1379	3626		41,000*	Cartridge case hole not centered
19	1354	3693		49,000	
20	1385	3610-		35,000*	Cartridge case hole not centered

	Velocity	Pressure	CLIENT
Average:	3706	48,350	
Extreme Var.:	195	20,000	
Mean Var.:			
Standard Dev.:			

RANGE CONDITIONS:	Barometer:	Date: Jul 15 1968
Dry Bulb Temp.:	Wind:	Range: O.D.L. (A-Range)
Wet Bulb Temp.:	Chronograph No.:	Gunner: Erby-Lehner
Rel. Humidity:	Screens: ECI	Recorder: Erby-Lewis

TABLE V. UNPLATED BARREL B

FIRING RECORD

AMMUNITION: Remington.220 Swift - Index 0822			
Case:	Used X:	Catalog No.:	
Primer:	Loader:	Lot No.: J03Y	
Powder: gr.	On:	Seating Depth:	
Bullet: 48 gr.		Overall Length:	
WEAPON: .220 Swift	Ser. No.: "B"	Bbl. Length: 27.25"	
Bore: .220 Groove: .224	Number:	Twist: 1/12	

Round No.	VELOCITY Time Over ft.	f.p.s. @	PRESSURE Loc Lc	p.s.i.	REMARKS
24	1276	3918		-	Plugged - Test
25	1282	3900		52,000	#400 Kistler Gauge
26	1309	3820		48,000	" " "
27	1302	3840		48,000	" " "
28	1275	3922		52,000	" " "
29	1266	3949		53,000	" " "
30	1282	3900		49,000	" " "
31	1310	3817		46,000	" " "
32	1328	3765		41,000	" " "(changed washer)
33	1313	3808		48,000	" " "
34	1306	3828		48,000	" " "

	Velocity	Pressure	CLIENT
Average:	3860.6	48,500	
Extreme Var.:	198	12,000	
Mean Var.:			
Standard Dev.:			

RANGE CONDITIONS:	Barometer:	Date:
Dry Bulb Temp.:	Wind:	Range:
Wet Bulb Temp.:	Chronograph No.:	Gunner: Erby-Lehner
Rel. Humidity:	Screens:	Recorder: Erby-Lewis

TABLE VI. TUNGSTEN PLATED BARREL - LENGTH 25.0"
ACCURACY AND AVERAGE MUZZLE VELOCITIES

Shot No.	220 Swift	Average Velocity (10 Shots) (fps)
1–20		3706
514–523	Group Size = 0.5"	3822
660–669	Group Size = 0.7"	3833
769–778	Group Size = 0.5"	3839
878–887	Group Size = 0.8"	3846
991–1000	Group Size = 0.9"	3831
1161–1170	Group Size = 0.7"	3808
1271–1280	Group Size = 0.8"	3750
1381–1390	Group Size = 0.6"	3726
1491–1500	Group Size = 0.65"	3736
Average		3790

Note: All velocities were recorded at 15' from muzzle.
Target was placed 40' from muzzle.

TABLE VII. TEST FIRING OF UNPLATED BARREL - LENGTH 27.5"

Shot No.	220 Swift	Average Velocity (10 Shots) (ft/sec)
24—34		3861
501—511	Group Size = 0.6"	3952
661—670	Group Size = 0.7"	3903
771—780	Group Size = 0.65"	3914
881—890	Group Size = 0.6"	3831
991—1000	Group Size 0.55"	3895
1161—1170	Group Size = 0.5"	3877
1271—1280	Group Size = 0.6"	3883
1381—1390	Group Size = 0.5"	3861
1491—1500	Group Size = 0.6"	3830
Average		3831

Note: All velocities were recorded at 15' from muzzle. Target was placed 40' from muzzle.

TABLE VIII. CONTROLLED ACCURACY TEST FIRINGS

W-plated Barrel G
Length 25.25"

No.	Muzzle Vel. (fps)
1	3650
2	3730
3	3720
4	3730
5	3760
6	3770
7	3760
8	3750
9	3800
10	3800
11	3800
Average	3780

Unplated Barrel B
Length 27.25"

No.	Muzzle Vel. (fps)
1	3850
2	3920
3	2880
4	3880
5	3880
Average	3880

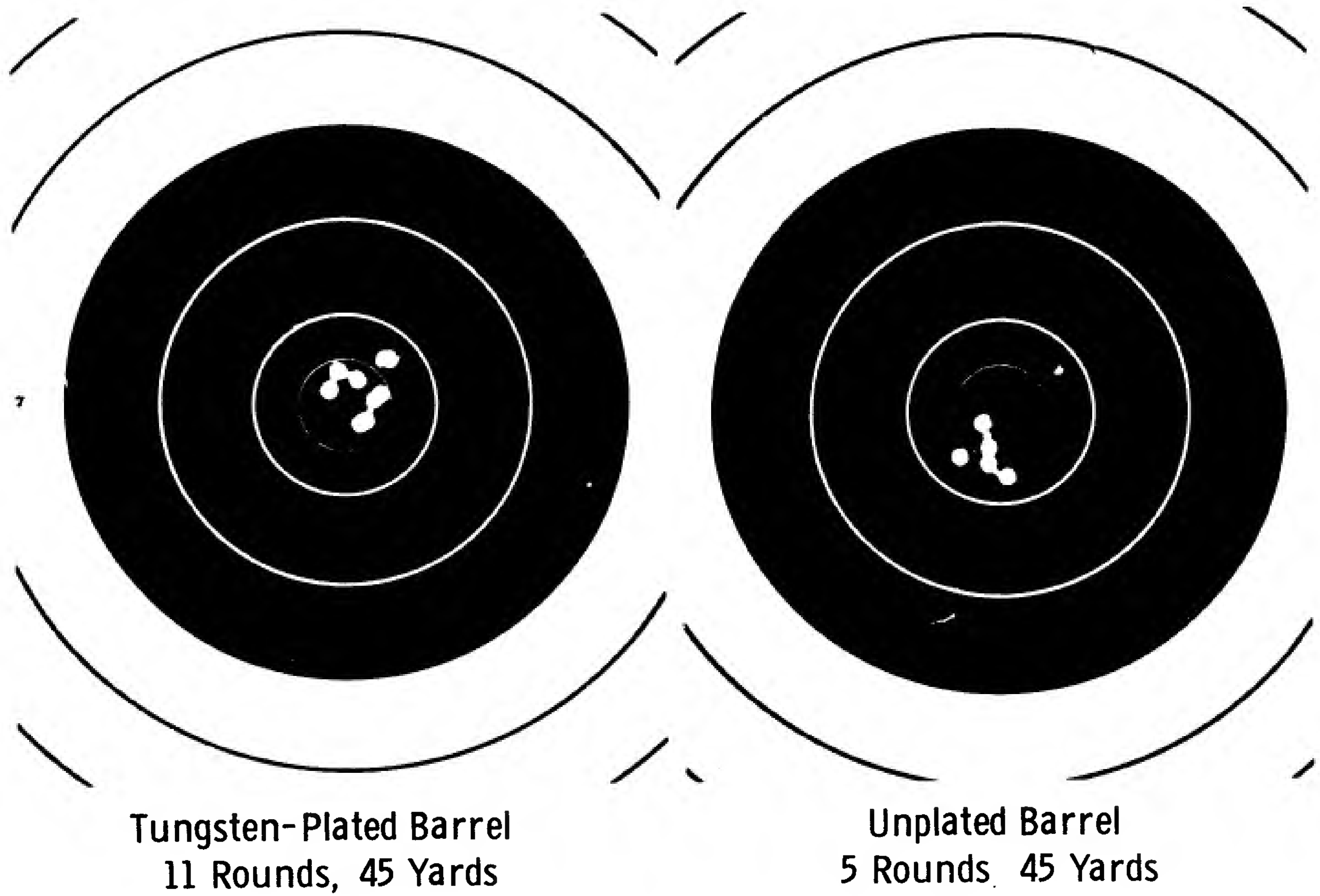

Figure 24. Target Cards From Controlled Accuracy Test Firings

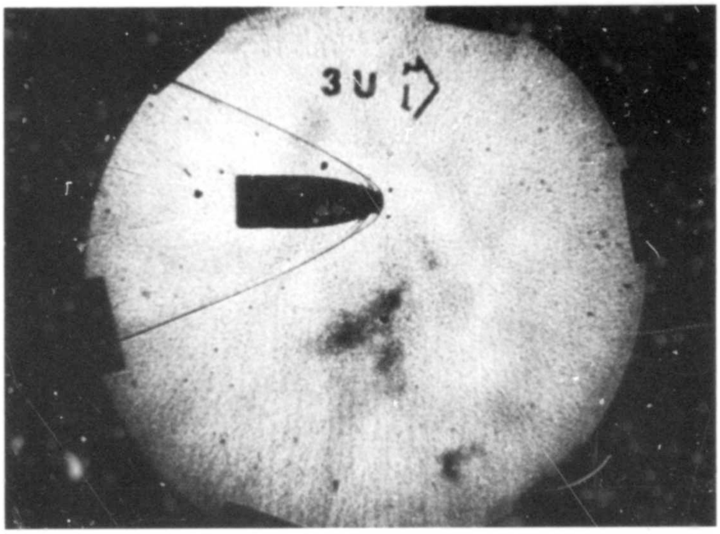

Figure 25. Photograph of Flying .220 Swift Projectile

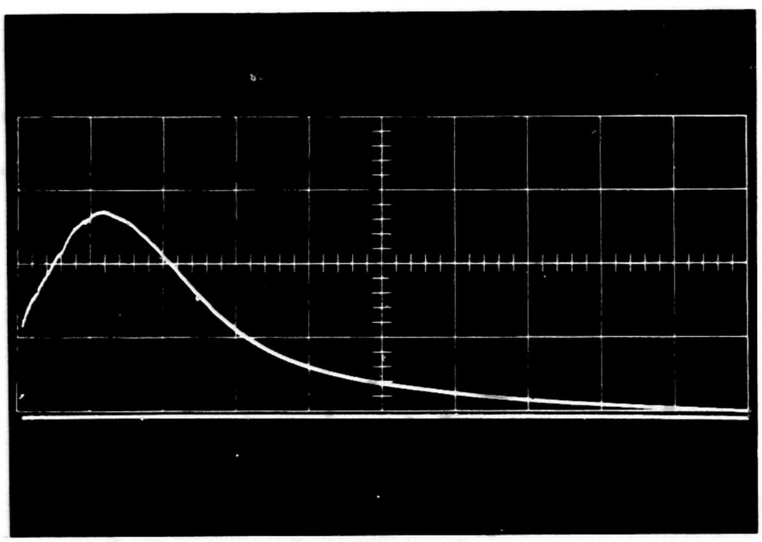

Figure 26. Pressure/Time Oscillogram Recorded by Kistler Gauge on Tungsten-Plated .220 Swift Barrel During Test Firing. Shot #5, Maximum Pressure 57,000 psi, Muzzle Velocity 3802 ft/sec, 48-grain Projectile

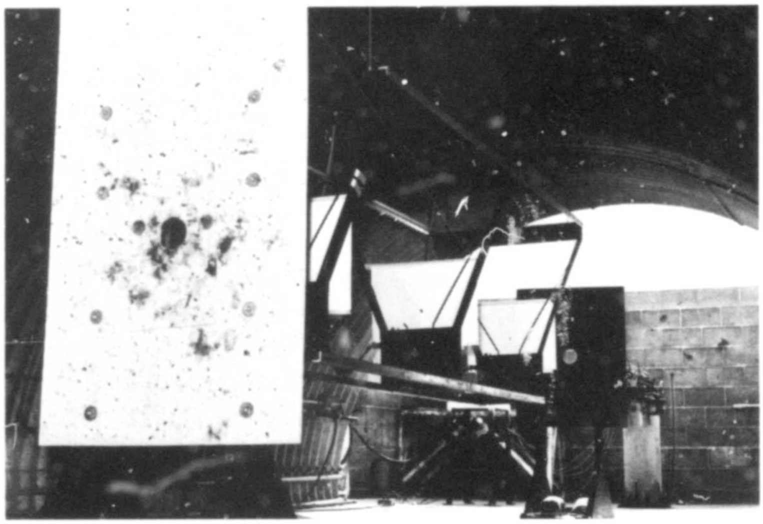

Figure 27. Instrumented Single-Shot Test Fixture

SECTION IX

HEAT TRANSFER COMPUTER STUDY

Symbols

ν	Temperature
K	Thermal conductivity
$\dot{Q}_s$	Heat input rate per unit area
C_p	Heat capacity
ρ	Material density
Δx	Thin slab increment
Δx_1	Surface slab increment
Δ_t	Small time increment

The study of heat transfer through thin tungsten platings is achieved by using a computer program which solves the equation of linear flow of heat:(A)

$$\frac{\delta^2 \nu}{\delta x^2} - \frac{\rho C_p}{K} \frac{\delta \nu}{\delta t} = 0 \qquad (5)$$

by finite-difference methods. The material is considered as several very thin slabs, of size Δx, and very small time increments Δt are used in conjunction with stability criteria. A finite difference formulation of Equation (5) is as follows:(B)

$$\frac{\nu_{i+1}^{n+1} - 2\nu_i^{n+1} + \nu_{i-1}^{n+1}}{(\Delta x)^2} - \frac{\rho C_p}{K} \frac{\nu_i^{n+1} - \nu_i^n}{\Delta t} = 0 \qquad (6)$$

$\nu_i^n \cong \nu(i\Delta x, n\Delta t)$: Temperature

(A) Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids, Oxford University Press, 1959.

(B) Richtmyer, R. D., Difference Methods for Initial-Value Problems, Interscience Publishers, 1957.

The computer program used is a general 1-dimensional heat transfer code, and has options to solve the above Equation (5) in cylindrical coordinates, with several materials and with arbitrary heat pulses. The program is written in FORTRAN IV and is run on the IBM 360 computer.

The heat pulse used in this study is approximately equivalent in shape and duration to those of the heat transfer study done at Cornell Aeronautical Laboratory.(C) The pulse used is shown in Figure 28. The integral of this pulse is equal to twice the average heat input per unit barrel area per shot - representative of the heat input at the breech, where maximum temperature will occur.

The heat is transferred to the surface slab increment Δx_1 by increasing its temperature as follows:

$$\nu_1^{n+1} = \nu_1^{n+1} + \frac{\dot{Q}_s \Delta t}{\rho_1 C_{p_1} \Delta x} \tag{7}$$

The heat then flows into the material according to Equation (6). Accuracy is achieved by using very thin slabs ($\Delta x = 0.1$ mil) and very small time increments.

The effect of a thin tungsten plating of the bore of a gun barrel is a reduction of the bore surface temperature during the high heat pulse of a single shot.

The maximum surface temperature increase at the breech for a solid-steel barrel is 1420°R for one shot; with a 0.002" layer of tungsten, the temperature increase is only 1020°R, a reduction of 400°R. This is due to the high thermal conductivity of tungsten - during the shot the heat is transferred rapidly through the tungsten, thus reducing the surface temperature. Thickening the tungsten will decrease this short-duration temperature peak. As seen in Figure 29, however, 2 msec after the shot the surface temperature is almost the same as for solid steel. The temperature of the steel-tungsten interface is given in Figure 30. It is seen that very little temperature gradient exists in the tungsten after 2 msec after the shot. The tungsten plating thus broadens and flattens out the heat pulse to the steel: maximum temperatures are reduced, but residual temperatures remain unchanged.

(C) F. A. Vassallo, D. E. Adams, and R. D. Taylor, "Caseless Ammunition Heat Transfer," Cornell Aeronautical Laboratory (CAL) Report No. GI-2433-Z-1, October 1967.

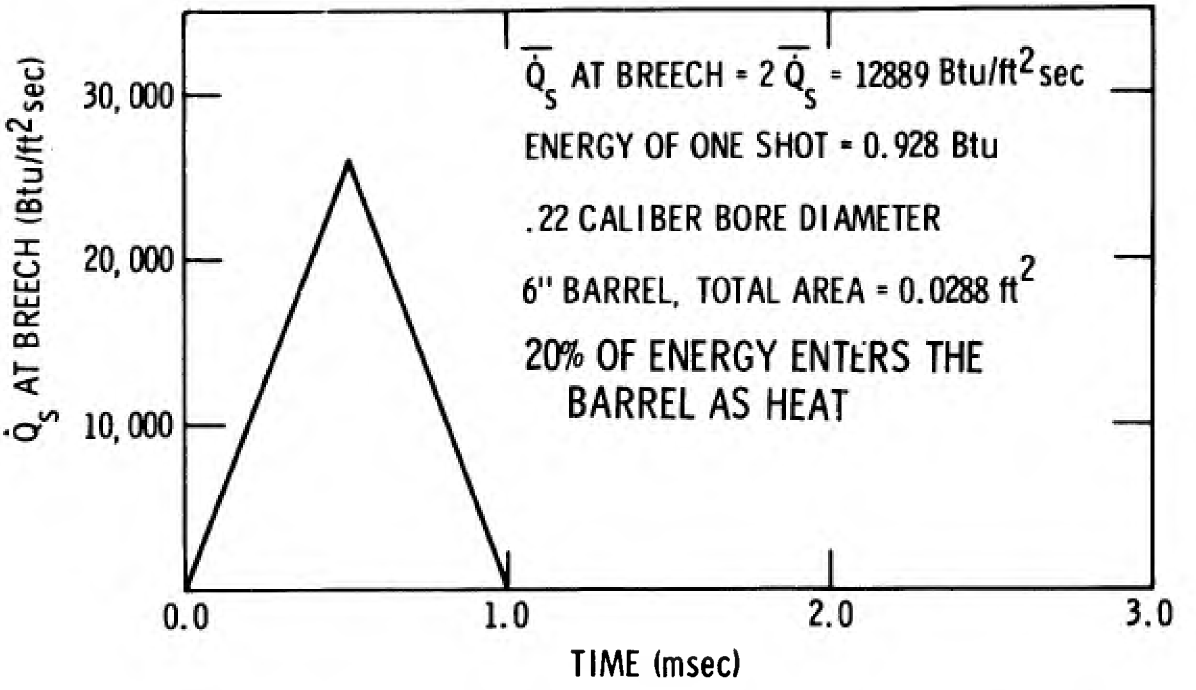

Figure 28. Heat Impulse of One Shot

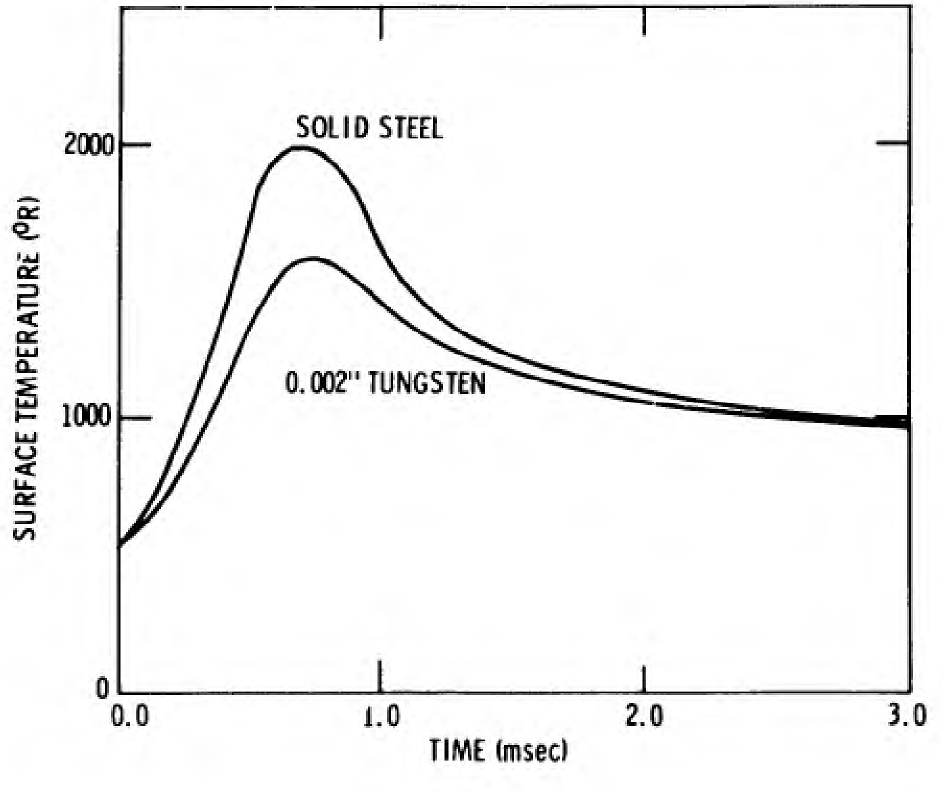

Figure 29. Comparison of Thermal Response at Surface of Solid Steel Barrel and 0.002" Tungsten Plated Barrel for One Shot

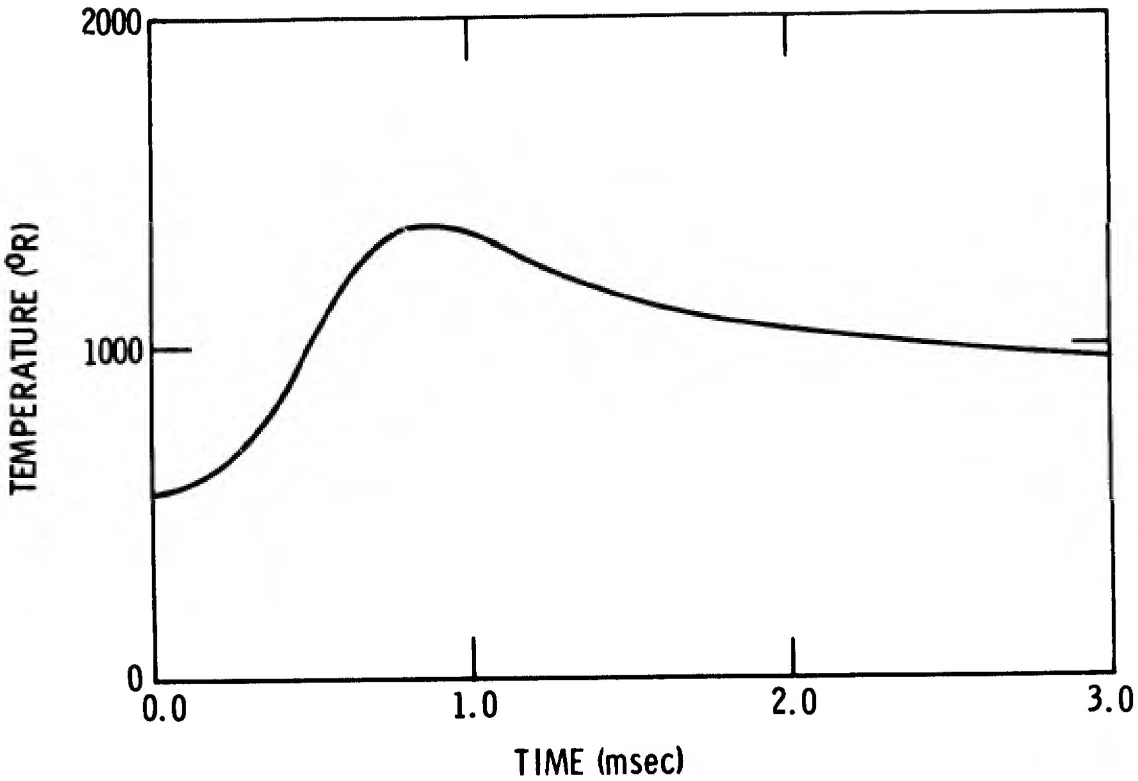

Figure 30. Temperature at Steel/Tungsten Interface for One Shot (0.002" Tungsten Plated Barrel)

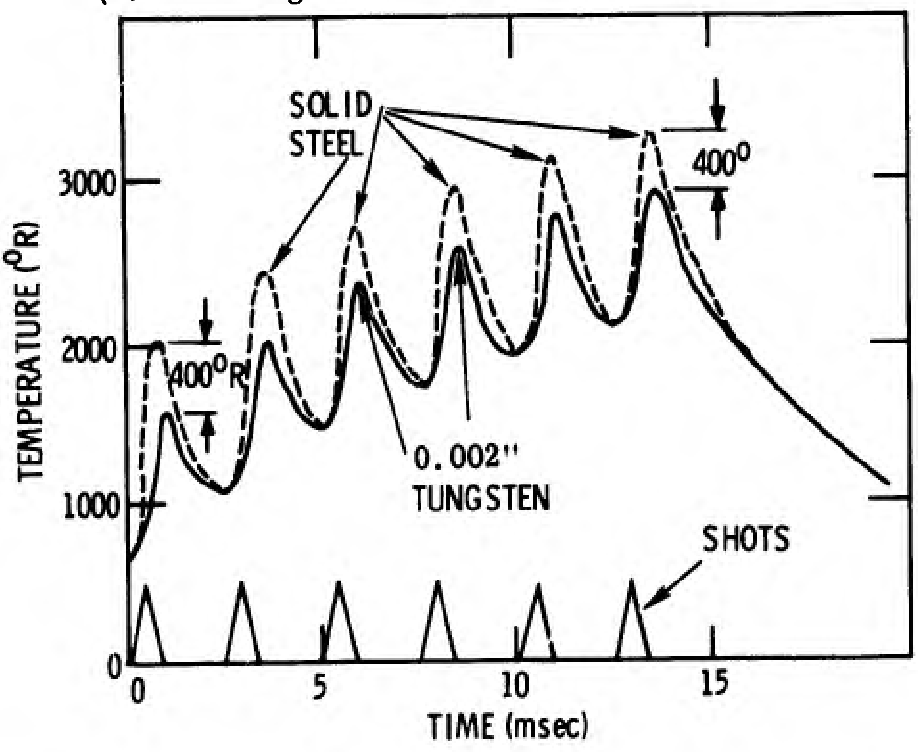

Figure 31. Temperature at Surface for Several Shots. Schematic Comparison of Solid Steel Barrel and 0.002" Tungsten Plated Barrel

The maximum temperature during a sustained rate of fire (which would occur during the last shot) would be reduced by a tungsten coating by the same amount as in a single shot (see Figure 31). The residual temperatures shortly after the shot would be the same, however, as the thin tungsten plating does not increase the total thermal capacity of the gun.

SECTION X

CONCLUSIONS

Under this program, it was demonstrated that tungsten coatings can be deposited with a firm metallurgical bond on the bore of .220 cal rifled barrels in predetermined and uniform thicknesses. Both a tungsten plated and an unplated .220 cal Swift rifle barrel were test-fired for 1500 rounds under the same conditions. Bore measurements during and after test firing showed that the plated barrel was less subject to erosion of the bore and over a shorter length than the unplated barrel. The test firing of the two barrels should be continued as soon as additional ammunition is available until erosion of the barrels exceeds the acceptable limit. It is believed that the erosion resistance of tungsten plated barrels can be further improved by detailed investigation of the correlation of deposition parameters and physical and mechanical properties of the tungsten plating and by proper "materials design" in form of depositing a tungsten plating with predetermined properties.

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13 ABSTRACT

A 0.004" oversized .220 cal rifled Swift gun barrel was plated with 0.002" of tungsten, thereby restoring its original bore size. The plated barrel and an unplated standard barrel were test fired with 1500 rounds of .220 caliber ~~Swift~~ Super Sport ammunition. This ammunition has a 48 grain projectile and was test fired at an average muzzle velocity of 3790 ft/sec with an average chamber pressure of 48,350 psi. The bore diameters as measured in both test barrels before firing and after firing 500, 1000 and 1500 rounds are listed in ~~Tables II~~ and III. As shown in these tables, less erosion was experienced over a shorter barrel length in the tungsten plated barrel than in the unplated barrel.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gun barrels						
Operational life of gun barrels						
Tungsten						
Plating with tungsten						
Vapor phase plating with tungsten						
Erosion of gun barrels past acceptable limit						
Interface tungsten-steel						

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